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Crop production risks in the Canadian prairie region in relation to climate and land resources

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Crop production risks in the Canadian prairie region in relation to climate and land resources

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The dots on the map represent Agriculture Canada research establishments.

SUMMARY

This study consists of a series of separate investigations, with the common theme of assessing and evaluating the production risks for grains and oilseeds in the prairie region. The first study describes and analyses current agricultural land uses in the region. Emphasis is on the configuration and adjustment of economic factors of production to the nature of the soil and climate resource base, particularly to different soils zones and soil textures (agroecological zones). This is followed by a study of long term (60 years) patterns of available soil moisture and other climatic indices. Results are expressed in terms of probabilities of events for each climatic variable, and interpreted in relation to drought frequencies and the use of summerfallow. The third study reports on the long term yield trends and yield variability for the major crops in the region in relation to weather and technology. The implications of this for drought analyses are examined. The fourth study examines the degree of land use flexibility (land use options or potential for diversification) that is inherent in the different agroecological zones in the region. It also compares current land use intensity with the projected potentials, and identifies areas where problems can be expected, as well as areas where agricultural activities could be expanded. An appendix describes the agronomic requirements for winter wheat in relation to the soil and climate resources of the prairies.

The study identifies the areas with the highest production risks, and defines the type and degrees of risk involved. It also discusses various risk management techniques, and comments on future possibilities for adjustment. The study identifies areas which currently are being over utilized, and others where the agronomic and economic potentials have not yet been reached.

There are several implications which emerge from this study:

- flexibility in cropping systems, relative to changing market demand, is important for long term agricultural viability. Diversification of cropping systems should be encouraged in areas where this is possible.

- opportunities in cropping flexibility and yield can be best realized by tailoring production systems to the natural characteristics of the environment.

- areas with abnormally high production risk, high risk of soil degradation and low suitability for agriculture should be farmed less extensively, or removed from production. Emphasis should be shifted to areas with greater natural opportunities, with concomittant shifts to land management practices which maintain or enhance soil quality.

- research is required to develop cropping systems (including tillage) which give improved economic returns while maintaining the quality of the soil. Such systems must be tailored to the natural characteristics of the production environments in the region, and they must ensure flexibility of crop choice to enable producers to adjust their production in relation to shifting market demand.

RÉSUMÉ

La présente étude comprend une série d'enquêtes distinctes ayant un thème commun: l'évaluation des risques de production pour les céréales et les oléagineux, dans la région des Prairies. La première enquête décrit et analyse les utilisations actuelles des terres agricoles dans la région. On y examine plus particulièrement la configuration et l'ajustement des facteurs de production économiques à la nature des facteurs pédologiques et climatiques, en particulier les différentes zones et textures de sol (zones agroécologiques). La deuxième enquête concerne le développement (e) à long terme (60 ans) des indices existants sur l'humidité du sol et d'autres indices climatiques. Les résultats sont exprimés en termes de la probabilité des événements pour chaque variable climatique et interprétés en fonction de la fréquence des sécheresses et de l'utilisation de la jachère d'été. La troisième enquête fait état des tendances à long terme du rendement et de la variabilité du rendement pour les principales cultures de la région par rapport au climat et aux techniques utilisées. On y examine les répercussions de ces tendances au regard des analyses de la sécheresse. La quatrième enquête étudie le degré de flexibilité lié à l'utilisation des terres (diverses utilisations des terres et possibilités de diversification) qui est inhérent aux différentes zones agroécologiques de la région. On y compare également l'intensité d'utilisation actuelle des terres avec la capacité prévue et on y identifie les régions où l'on prévoit des problèmes et celles où l'on pourrait intensifier les activités agricoles. En annexe, on décrit les exigences agronomiques du blé d'hiver par rapport aux facteurs pédologiques et climatiques des Prairies.

L'étude identifie les régions où les risques de production sont le plus élevés et définit le genre et le niveau de risques dont il est question. On y examine également diverses techniques de gestion des risques et les possibilités d'ajustement futures. Enfin, on identifie les régions qui sont actuellement surexploitées et celles où les possibilités agronomiques et économiques ne sont pas encore totalement développées.

La présente étude permet plusieurs constatations:

- Il est important que les systèmes de culture soient souples et qu'ils s'adaptent à la demande du marché qui change, si l'on veut que l'agriculture soit rentable à long terme. Il faudrait encourager la diversification des systèmes de culture dans les régions où cela est possible.

- On peut le mieux tirer profit de la souplesse des systèmes de culture et optimiser les rendements en modelant les systèmes de production sur les caractéristiques naturelles de l'environnement.

- Il faudrait exploiter de façon moins intensive ou retirer de la production les régions qui présentent des risques de production anormalement élevés et des risques élevés de dégradation du sol et qui ne conviennent pas tellement bien à l'agriculture. Il faut plutôt encourager l'exploitation des régions qui ont de plus grandes possibilités naturelles ainsi que l'adoption de pratiques de gestion des terres permettant de maintenir ou d'améliorer la qualité du sol.

- Il faut faire des recherches afin de mettre au point des systèmes de culture (y compris le labourage) qui permettent une augmentation des recettes tout en maintenant la qualité du sol. De tels sytèmes doivent être adaptés aux caractéristiques naturelles des milieux de production de la région et offrir aux producteurs le choix de leurs cultures afin qu'ils puissent harmoniser leur production avec la demande du marché qui est changeante.

ACKNOWLEDGEMENTS

This study was undertaken by the Land Resource Research Centre as part of the ongoing research in agricultural land evaluation and biological production potentials. The objective of the study was to assess and describe the types and degree of crop production risks inherent in the climate and soil resources in the prairie region of western Canada, in relation to the production systems currently being utilized in that area. In this way some of the necessary adjustments to production could be estimated.

The project team, consisting of the authors of the report and associated other staff, met on a regular basis throughout the project. Ideas and workplans for each phase of the project were put forward by each contributor. These were debated and evaluated by the team, and adjustments were made as necessary. Final decisions were based on the collective wisdom of the group.

The authors wish to acknowledge the considerable contributions made by other staff of the Land Resource Research Centre. In particular the authors are in debted to Mr. D.Z. Chaput and his group for analyzing the tremendously large volumes of data required for this project and to K. Loebel and L. Houwing for their assistance. Also the advice and guidance of Dr. J.A. Shields, the contributions of the cartography section in preparing the figures and maps, and the typing of the manuscript by L.M. Howe and S.D. Roy are gratefully acknowledged.

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PERSPECTIVES ON AGRICULTURAL RESOURCES IN THE PRAIRIE REGION OF WESTERN CANADA

J. Dumanski

The production of grains and oilseeds is the dominant agricultural activity in the prairie region of western Canada. In Saskatchewan, Alberta and Manitoba grains and oilseeds account for 70%, 41% and 56% of farm cash receipts respectively (Statistics Canada, 1987). The relative importance of these commodities, however, is 50% to 100% greater if one includes the value of products consumed on-the-farm as livestock feeds. The approximately 145,000 Canadian Wheat Board permit holders produce over 50 million tonnes of grains and oilseeds annually.

The grains and oilseeds sector in the prairie region is largely export oriented, which makes this sector particularly vulnerable to the vagaries of the international market place. In recent years foreign intervention in the market place, particularly by the United States and the European Economic Community, have severely depressed world prices for cereals and oilseeds. This, plus the many years of high interest rates, have precipitated severe financial difficulties for many producers. The grains and oilseeds sector, and by implication the prairies, have been the most severely affected. The prairie provinces account for over 60% of the farms which are in financial difficulties, and Saskatchewan and Alberta have more than one-half of the total number of Canadian farms that are experiencing serious financial problems. (Farm Credit Corp., personal communication). This financial stress is caused by falling returns, falling asset prices, rising operating costs and rising debt loads.

In addition to this financial uncertainty, the prairies have been subjected to considerable environmental stresses within the last few years. The prairie agricultural sector is dominated by dryland production, and thus it is highly dependent on moisture from annual precipitation. However, severe droughts have been frequent during the past 5 years, and these have had devastating effects in the localities affected. At the same time, soil degradation, in the form of wind and water erosion, salinization and organic matter loss, has been accelerating in many parts of the region. As would be expected, wind erosion was most severe in regions that were most affected by the drought. A recent study (Dumanski et al., 1986) estimated that about 6.3 million hectares of agricultural land in the prairie area is affected by moderate and severe wind erosion, and 4.6 million hectares are affected by moderate and severe water erosion. Salinity affects about 2.2 million hectares.

Problems, adversity and risk are not unusual in the prairie grains and oilseeds sector. However the problems in recent years are more severe than normal. It is obvious that some adjustments in this sector are necessary, but it is not clear what these should be, when they should be instituted nor by whom. This study was undertaken to provide some of the necessary background for such decisions.

The study consisted of a series of separate investigations, all with the common theme of assessing and evaluating the production risks for grains and oilseeds in the prairie region. The results of each investigation are reported in the body of this report; summaries of each section are provided in this paper. The report begins with a description and analysis of current agricultural land uses in the region. Emphasis is on the configuration and adjustment of economic factors of production to the nature of the soil and climate resource base, particularly to different soil zones and soil textures (agroecological zones). This is followed by a study of long term (60 years) patterns of available soil moisture and other climatic indices. Results are expressed in terms of probabilities of events for each climatic variable, and interpreted in relation to drought frequencies. The third study reports on the long term yield trends and yield variability for the major crops in the region in relation to weather and technology. The implications of this for drought analyses are examined. The fourth study examines the degree of land use flexibility (land use options or potential for diversification) that is inherent in the different agroecological zones in the region. It also compares current land use intensity with the projected potentials, and identifies areas where problems can be expected, as well as areas where agricultural activities could be expanded. The appendix describes the agronomic requirements for winter wheat in relation to the soil and climate resources of the prairies.

HIGHLIGHTS OF THE "PHYSICAL AND ECONOMIC STRATEGIES OF FARMING IN THE MAJOR SOIL ZONES OF THE CANADIAN PRAIRIE REGION"

The land resources of the prairie region for crop production have been summarized by Acton et. al. (1980). The major agricultural soils are the Brown, Dark Brown, Black and Dark Gray Chernozemic soils. These soils are distributed in somewhat of a concentric manner around the driest area (Brown Chernozemic), and reflect a climate sequence related to increased available moisture, which radiates outward from this area. Within this sequence the Black Chernozemic soils have the highest yield potentials.

Other soils used for field crop production are Solonetzic soils in the south, Solodic soils in the Peace River area and Gray Luvisolic soils along the northern agricultural fringe. Acton et. al. (1980) estimated that essentially all of the suitable soils are already in production, and that any further increases in production will come from better utilization of existing land, rather than from new land clearing.

The evidence of this study shows that the physical environment for crop production, soils and climate, has a major influence on farm configuration and crop distribution. It demonstrates that farmers have made considerable adjustment in management practices and farming patterns in relation to the heat and moisture availability sequence demonstrated by the different agroecological zones, and that they have made investments that optimize production potentials. Farm size is dramatically larger in the Brown and Dark Brown Chernozemic areas than in the other regions, and decreases progressively to the north. The differences in the proportion of rented land and the percent of farmland cultivated is less dramatic, but the trend is towards decreasing values towards the north.

Spring wheat, oats, barley and summerfallow are the dominant land uses in the region, but their proportional distributions vary dramatically among the different agroecological areas. The proportions of wheat and summerfallow are highest in the driest and warmest regions, and decrease regularly to the north. The area of oats, barley, and tame hay shows the converse distribution, with low proportions in the south and generally increasing amounts towards the north. A similar but less regular distribution is observed for oilseeds. Improved pasture, on the other hand, is generally similar in all areas, except on Gray Luvisols where it is dramatically higher.

The economic variables, capital investment and income and expenses, deviate from this pattern somewhat, and tend to more closely reflect market potentials and opportunities. Earlier studies (Dumanski and Stewart, 1981; Acton et. al, 1980) identified the Black Chernozemic soil region as the area with the highest comparative production potential, with gradually decreasing potentials to the south because of decreased moisture availability, and to the north because of decreased heat and growing season length. This study shows that capital investment and total sales per cultivated hectare tend to be highest in the Black Chernozemic area and lower to the south and north. However, operating expenses are considerably lower in the southerly areas, with the result that gross margins are relatively similar for the Brown, Dark Brown and Black Chernozemic soils, but considerably higher than in the Dark Gray Chernozemics and Gray Luvisols. The tendency towards lower operating expenses in the south, particularily lower fertilizer inputs, reflects the unreliable crop response to these inputs in these areas, as a consequence of unreliable precipitation during the growing season. Farmers in these regions tend more to utilize crop residues, along with higher proportions of summerfallow, as the main hedges against these higher production risks. By controlling input costs and other operating expenses, farmers can maintain acceptable levels of profitability (other things being equal), at least in the short term. This, however, is often achieved at the expense of more rapid depletion of soil quality.

HIGHLIGHTS OF "CLIMATE RISK ANALYSES OF THE PRAIRIE REGION"

The amount, timing and variability of precipitation events are critical factors in rainfed agriculture in the prairie region. This study used a modified form of the Versatile Soil Moisture Budget to describe the spatial and temporal variability of soil moisture at seeding and at heading for wheat-fallow rotations and continuous wheat. Water content at seeding for the fallow year, accumulated moisture stress indices for wheat from seeding to harvest and from jointing to soft dough and seasonal water deficits for wheat and for perennial forages were also evaluated. Results were expressed in terms of a "standard" loamy soil (150 mm AWC), and on probability levels based on 60 years of data from 27 weather stations. Regression equations are provided for calculating these and other variables for a range of soil textures. In addition, biometeorological time scales were used to simulate maturity stages in wheat and barley.

In addition to describing the spatial and temporal variability of the climate resources of the area, the results of this study provide a detailed assessment of the effects of summerfallowing as a technique to better manage production risk associated with climate. They also provide a means for assessing the frequency of drought and estimating some of the impact.

On the average, the greatest amount of water conserved in loamy soil due to summerfallowing is achieved in the Dark Brown Chernozemic zone, the southern portion of the Black Chernozemic zone and the northern portion of the Brown Chernozemic zone (30-36 mm). This decreases rapidly to about 14 mm in the driest area and to about 6 mm to the north. Clayey soils with high available water capacity (AWC) are more effective in conserving water under fallow than are sandy or loamy soils. However the additional water conserved is 2 to 4 times higher in the more moist areas than in the driest areas of the south. In many cases the extra water conserved by summerfallowing on high AWC soils in wetter zones can be detrimental for early seeding. Average yield increases attributed solely to extra moisture conserved by summerfallow are estimated to be about 112 to 280 kg depending on the area. The influence of summerfallow does not carry over beyond one crop year.

In most zones the probability of water contents at heading being less than 50% of AWC is 80% or more, indicating that some water stress is experienced in most areas in most years. Summerfallowing lowers these probabilities only slightly on sandy soils, but the effect is quite significant (10 to 20%) on clayey soils. The probability of extreme moisture stress at heading (water content less than 10% of AWC) ranges from near zero in the wetter areas, to 40-60% in the driest climatic zones.

Indices of water stress, based on comparisons between actual and potential evapotranspiration were calculated for various plant phenological stages and according to the various AWC's. Water deficits (or aridity indices) were also determined, based on the total amount of water required to maintain soil water above 50% of AWC during the growing season. The frequency and probability of drought were then calculated by defining drought according to certain threshold values of these indices for specific crops. Assuming that a water deficit of 350 mm or more constitutes a serious drought for wheat on loamy soils, then this event occurs with a return period of 5 years or less in the driest areas, ranging upward to 20 years or more in the more humid regions. Similarily assuming that a deficit of 450 mm is a serious drought for forages, then the return period for this ranges from 1.5 to 2 years or less in the driest areas, to greater than 10 years in central and northern areas. Soil texture can have significant impact on these probabilities in a local area, but its effect is small overall in comparison to geographic location. The probability of achieving critical threshold values was significantly higher for continuous wheat than for wheat-fallow rotations.

Average thermal resources for maturing wheat and barley were found to be adequate in most regions used for agriculture today. However in more northerly areas first frost occurred before ripening of wheat with a return period of 10 years or less. The analysis however did not consider the time required to complete the harvest.

HIGHLIGHTS OF "RISK ANALYSIS OF CEREAL YIELDS IN THE CANADIAN PRAIRIE REGION"

A crop growth model combined with regression analysis was used to study weather and technology time trends in cereals and oilseeds (canola) for the period 1961-82. Results were evaluated according to the different soil zones in the prairie region.

Results indicate that yields increased regularly in all soil zones up to 1975, but they began to level off thereafter. The yield increases were relatively similar for all zones and averaged approximately 800 kg/ha over the 22 years of the study. However the largest comparative yield increases occurred in the Brown Chernozemic soil zone, followed by the Dark Brown Chernozemic and then the Black Chernozemic zone. The effect of technology factors appeared to be of about the same magnitude in all zones. The reason for the levelling off of yield after 1975 could not be determined from the data used in this study. There was no clear evidence that the climate changed significantly so as to increase or decrease yields during this time period.

Considerable annual variability in yields was observed in all soil zones. Yield variability was the highest in the Brown soil zone in Saskatchewan, and the lowest in the Black soil zone in Alberta. Cyclic time sequences of yield were evident in all areas. These indicate that a return period of 18-22 years may apply for major droughts in this region. There was some evidence to indicate reduced annual yield variability from 1966 to 1982, compared to the preceeding period.

The study of yield probabilities indicated a higher probability of obtaining a yield of 1000 kg or less in the drier areas of the south than in the more humid areas of the north. Differences between zones was not as great as expected because of the larger use of summerfallow in the south. Probabilities for 1000 kg or less increased by a factor of two for crops seeded into stubble and gave a more accurate indication of differences in climate between the north and south.

Regression analyses indicated that yield trends and variability for oats and barley are similar to those of wheat, and that similar conclusions could be inferred for these crops. This, however, was not the case for oilseeds (canola), and a separate analysis will have to be conducted.

HIGHLIGHTS OF "ASSESSING THE PHYSICAL LAND FLEXIBILITY OF THE PRAIRIE REGION OF WESTERN CANADA"

The current financial and environmental (degradation) difficulties being experienced by farmers in the prairie region indicate that adjustments in current agricultural land use and land management are required. However, it is not clear what these changes should be, and where they would be the most effective. This study in physical land flexibility (alternate land use potentials) describes the inherent opportunities in the region for land use diversity and identifies areas for possible land use adjustment.

Estimates of land flexibility are provided in two ways. The first is based on classical soil and climate suitability techniques. Thus the area with the highest number of suitable crops has the highest flexibility.

The second approach, called physical land flexibility (PLF), involves the development of an index of flexibility which incorporates estimates of potential yields with estimates of how much land considered as suitable could be used for the crops. A total of eight crops are used in the study: spring wheat, oats, barley, canola, corn, soybean, sunflower and phaseolus bean. Also, current land use for the cereals is compared with PLF values for these crops to identify regions where land use adjustment is necessary.

Based only on classical soil and climate suitabilities, southern Manitoba has the highest potential for crop diversification, followed by east central and northern Saskatchewan. The largest part of the remainder of the prairie region is suitable for only four of the eight crops studied, these being the cereals and canola.

Estimates of physical land flexibility (PLF), on the other hand, indicated that the highest flexibility occurs in the Black Chernozemic soils, followed in decreasing order by the Dark Gray, Dark Brown and Brown Chernozemic soils. PLF values in the Black Chernozemics are four times higher than the Brown, two times higher than the Dark Brown and 20% higher than the Dark Gray Chernozemics. PLF values increased directly with clay content in the soils; the highest values were found in clayey soils in the Black Chernozemic zone and the lowest in sandy soils in the Brown Chernozemic zone.

A comparative index was established based on the PLF value for the Red River Plain. This area has the highest PLF value in the prairie region, and it was used as the standard against which all other areas were compared. On this basis the potential flexibility in southern Manitoba was within 80% of the Red River Plain, central Saskatchewan and eastern Manitoba were within 60-80%, and eastern and northern Saskatchewan, western Manitoba and western and northern Alberta were within 40-60%. The largest portion of the remainder of the prairie region, however, had less than 40% and often less than 20% of the flexibility of the Red River area.

A flexibility ratio based on comparing actual to potential land flexibility for cereals only, was also calculated. This indicated that sandy soils in all regions are probably overutilized, along with loamy soils in the Brown Chernozemic zone. Some reduction of production, in terms of additional forage rotations or removing land from production, could be visualized in these areas. The major areas affected are southwestern Saskatchewan, eastern Alberta, southwestern and eastern Manitoba and the northern agricultural fringe.

On the other hand, the potential in certain areas of the prairies is being underutilized, particularily in eastern Saskatchewan, western Alberta and the Peace River area. Some intensification of production could be visualized in these areas. In general terms the potential is most underutilized in the Black Chernozemic soils, followed in decreasing order by the Dark Gray, Dark Brown and Brown Chernozemic soils

CONCLUSIONS

This study demonstrates that land use adjustment to the different agroecological zones in the area accounts for a considerable amount of the physical and economic evolution in the cropping patterns in the prairie region. This evolution, initiated after the dust bowl conditions of the 1930's and fuelled by capitalization, mechanization and innovative research, was achieved in accordance with farmer's understanding of production risks and the relatively favourable market conditions of the past. The area with the highest production risk is in the arid to semi-arid region of the south, where summerfallowing, crop residue recycling and low annual inputs have been the predominant techniques employed.

Current markets, however, have changed considerably, and as a consequence this process of adjustment has not yet run its course. Inequalities in national and international markets, falling land values and exaggerated input costs in relation to returns are distorting some natural advantages in certain areas. Currently there are areas being overutilized, whereas others are underutilized. At the same time some tillage and land management techniques are resulting in enhanced degradation of the soil, thereby affecting the long term production potential of certain regions.

It is important to realize that further advances in agriculture will be achieved through better utilization of land already in production. Within this situation cropping systems must be better matched to the inherent production environments in specific areas, so as to optimize the natural opportunities present in these areas while reducing the effects of constraints.

This study indicates that agriculture in the Black Chernozemic zone has not yet reached its agronomic or economic potential. Some intensification of agriculture could be undertaken in these regions. Conversely some areas, particularily in the Brown Chernozemic and Gray Luvisolic zones, should be utilized at lower intensity levels than at present, or removed from cultivation.

Concerning soil management, results from the study point to the possibility of some further reductions of summerfallowing in the more humid regions. In the more arid areas, however, and barring any major breakthroughs in moisture conservation, some small reduction might be possible on the clayey soils, but in other areas this will be much more difficult. This is because of the high natural probability of drought in these areas. In all regions of the prairies, there is considerable potential for more balanced soil water management in relation to crop needs, improved crop husbandry, and improved fertilizer and crop residue management. Northern areas would benefit from shorter season and higher quality cultivars.

There are several implications which emerge from this study. These can be summarized as follows:

- flexibility in cropping systems, relative to changing market demand, is important for long term agricultural viability. Diversification of cropping systems should be encouraged in areas where this is possible.

- opportunities in cropping flexibility and yield can be best realized by tailoring production systems to the natural characteristics of the environment.

- areas with abornmally high production risk, high risk of soil degradation and low suitability for agriculture should be farmed less extensively, or removed from production. Emphasis should be shifted to areas with greater natural opportunities, with concomittant shifts to land management practices which maintain or enhance soil quality.

- research is required to develop cropping systems (including tillage) which give improved economic returns while maintaining the quality of the soil. Such systems must be tailored to the natural characteristics of the production environments in the region, and they must ensure flexibility of crop choice to enable producers to adjust their production in relation to shifting market demand.

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A DESCRIPTION OF PHYSICAL AND ECONOMIC STRATEGIES OF FARMING IN THE MAJOR SOIL ZONES OF THE CANADIAN PRAIRIES

E. HUFFMAN

The adaptation of farm production systems to the soil-climatic regimes under which they operate is generally well advanced in Canada. Just as broad associations of crops and regions, such as fruit in Niagara, or wheat in the Prairies, are well established in our understanding of agricultural production and environment, more specific and localized associations are recognized by persons familiar with an area. For example, the Brown Chernozemic soil zone of the Prairies is generally considered to be dominated by "large, highly mechanized, low input, wheat-fallow" production systems, while farms in the Black Chernozemic zone are viewed as smaller, more intensive, more diversified and more productive. However, documentation of these differences, especially in terms of an holistic economic and physical view, is not readily available. This paper reports on a study conducted using Census of Agriculture data to examine the extent to which socioeconomic characteristics differ with respect to the broad physical conditions characteristic of the main soil zones of Alberta, Saskatchewan and Manitoba.

Census of Agriculture data have been used often in the past in farm and regional typology schemes. Economic and product-type classifications of farms in census reporting areas have been carried out since the early days of consistent census data collection (McArthur and Coke, 1939; Hudson et al., 1949), while more recently, complex statistical procedures have been used to delineate farm regions based on a large number of characteristics (Laut, 1974; Dumanski et al., 1982). The study by Dumanski and colleagues employed cluster analysis to develop crop groups, which were then interpreted with respect to soil Great Groups. However, analysis of economic or social conditions common to the crop groups was not done. The present study starts with the regionalization provided by the zonal Great Groups (Brown, Dark Brown, Black and Dark Gray Chernozemics and Gray Luvisols) as presented on the 1:5 M Soils of Canada map (Clayton et al., 1977), and analyses the similarities and differences among 'average farms', using variables such as farm size, capital investment levels and annual income, expenses and gross margins.

METHODS

Descriptive statistics were compiled for each of the soil zones from a 1981 Census of Agriculture database listing summary statistics for each soil map polygon. This database had been prepared by overlaying Census Enumeration Area (EA) maps on the Soils of Canada map, coding appropriate EA's (those with 60% or more of their area) to each polygon and generating a statistical profile of an 'average' farm for each soil polygon. Since it was not possible to access the individual farm records for farms within each soil zone, these 'statistical farms' were treated as observations.

The selection of 'representative' EA's dictated that only values based on a sample, such as means or medians (mean % of farmland in grain, or mean farm size, for example) were acceptable for characterization purposes. Absolute values, such as the total area of farmland within a polygon, were not obtainable. Estimates were based on only those polygons which conformed to the zonal pattern of the Brown, Dark Brown, Black and Dark Gray Chernozemic and the Gray Luvisolic soils. (Fig. 2.1). These Great Group comparisons were then refined using the textural groupings sandy, clayey and loamy within each Great Group.

The farm characteristics selected for description of zones included: farm size, cultivated land as a percentage of farm size each crop type as a percentage of cultivated land, the dollar value of total capital investment (land, buildings, machinery and livestock) per cultivated hectare and by composition (% machinery, % livestock) and operating expenses (all cash expenses such as feed, fuel, chemicals and hired labour, but not interest on loans, depreciation or return to operator labour), total sales, gross margin (total sales minus operating expenses) and fuel and fertilizer costs per cultivated hectare. Additional variables included total sales per dollar of investment and total sales per dollar of operating expenses.

The statistic used to describe each variable depended on the nature of the characteristic. The arithmetic mean was used for physical variables such as farm size and crop percentages, whereas the median was used for the economic variables (capital values, expenses and sales, etc.). The median reduced the effect that extreme values had on the result, so that an individual farm such as a $2 million hog operation involving only two hectares did not skew the results.

Data from the 1981 Census of Agriculture for physical variables (farm size, crop areas, etc.) refer to 1981, while economic variables are given for 1980. Since both 1980 and 1981 are considered 'normal' years in terms of weather conditions (R. DeJong, pers. comm.) and grain yields (unpublished data, LRRC), Census of Agriculture data are representative of average socioeconomic conditions with respect to agricultural production. The values (especially economic) can be expected to change from year to year, but relationships between different areas should remain relatively constant.

RESULTS

Approximately 125,000 or 81% of all prairie farms were captured in the EA - Polygon file. The area under study (agricultural areas of Manitoba, Saskatchewan and Alberta) consisted of 201 polygons with at least ten farms each, and the number of farms included in the analysis ranged from ten(minimum for confidentiality) to 10546 per polygon. Most polygons were represented by between 100 and 500 farms each. In order to ensure comparability the study was restricted to dryland operations, with the result that nineteen polygons, each with a mean of greater than 1.5 percent of cultivated land under irrigation, were

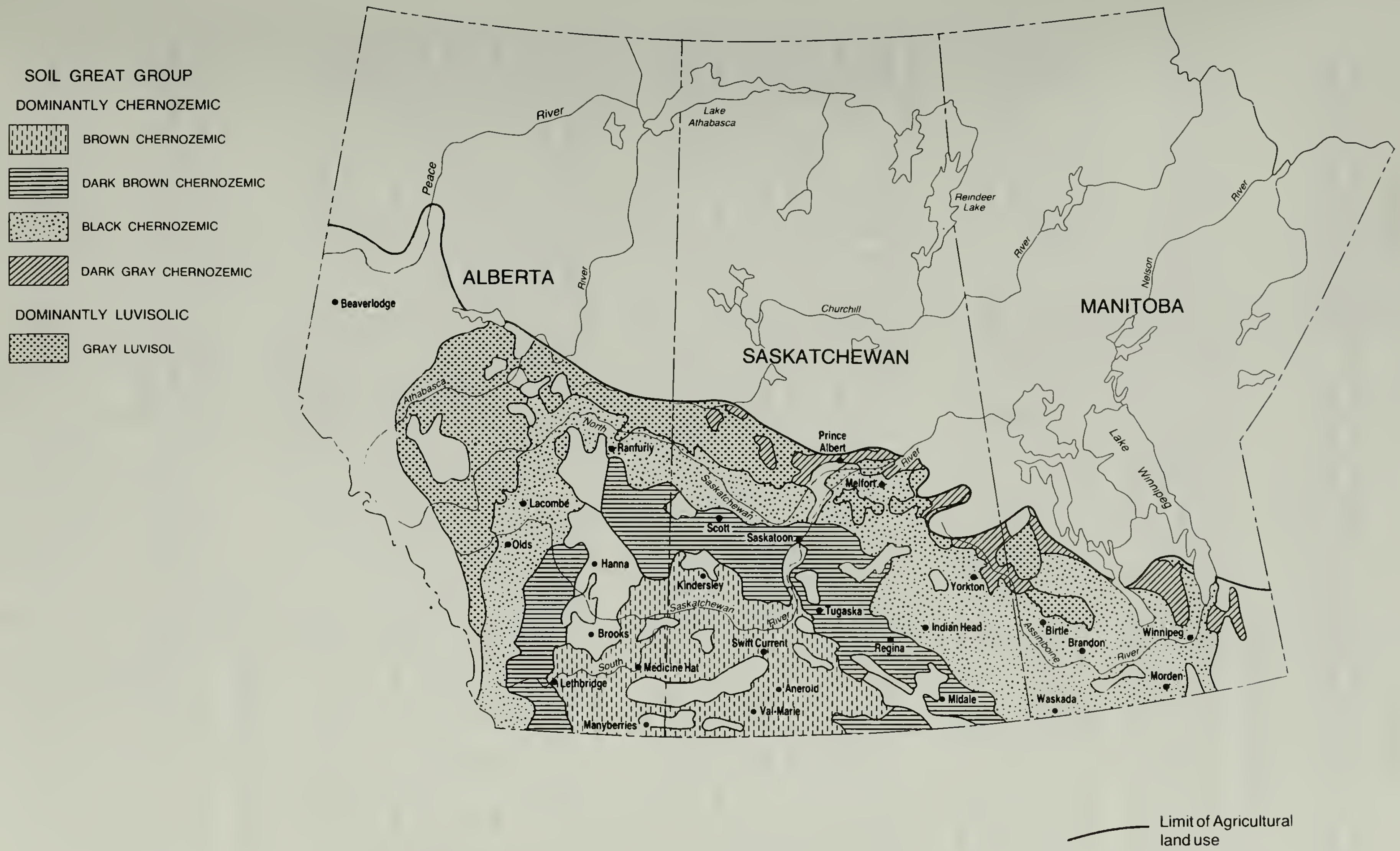


Fig. 2.1 Distribution of Zonal Soil Great Groups of the Canadian Prairies. Blank areas were not analyzed because of insufficient data.

LRRC

deleted from the analysis. In addition, 30 polygons that were not considered to be representative of the general 'zonal' pattern of their respective Great Groups were deleted.

Brown Chernozemic Soils

The Brown Chernozemic soils of the Great Plains occupy approximately 96,000 km^2 in southern Saskatchewan and Alberta. This is typically the driest portion of the prairies and dryland wheat farming and ranching are the standard agricultural activities.

Dryland farming in this soil zone is extensive and specialized in spring grain production. The farms are generally large, with a high proportion of farmland cultivated and a predominance of spring wheat and summerfallow in the production system (Table 2.1). The proportion of oilseeds is very low, oats and barley are relatively scarce and hay and improved pasture constitute only 6.0%.

According to the 1981 Census, farms in the Brown soil zone were comparable to those in the Dark Brown and Black Chernozemic soil zones in terms of gross margins, with total sales averaging $130/ha, operating costs $42/ha and gross margins $85/ha. Total capital value was relatively low and was distributed 80% to land and buildings, 16% to machinery and 4% to livestock. The total sales to investment ratio indicates that even though capital investment was low it was used only moderately effectively in generating income compared to farms in the Dark Brown and Black zones. However, farms on the Brown soils had a very high sales to operating expenses ratio, meaning that annual operating expenses were used very efficiently. This high efficiency was a function of low fuel consumption and low fertilizer use.

Differences were found between farms on clayey and loamy textured soils (sandy soils are underrepresented) in the Brown Chernozemic soil zone, particularly in the size of farms, the proportion of land cultivated and in the economic parameters. Farms on loamy soils were approximately 35% larger (Table 2.2), while farms on clayey soils had about 7% more of their farmland cultivated. Capital investment per hectare was about 20% higher on clayey than on loamy soils, total sales per hectare were 5% greater, operating expenses were 9% higher and gross margin per hectare averaged 3% more. Fuel costs were approximately equal, while fertilizer use on clay soils tended to be higher than on loamy soils. In terms of economic efficiency, farms on loamy soils showed better results, with 11% better use of investment dollars and 2% better use of annual operating expenses.

Dark Brown Chernozemic Soils

The Dark Brown Chernozemic soils cover approximately 107,000 km^2 in Alberta and Saskatchewan. Agricultural production is generally dryland cropping of spring grain, with small amounts of oilseeds and winter grains and some cattle.

Cropping patterns on the Dark Brown soils differed slightly from those on the Brown, but the mean farm size was approximately the same.

Table 2.1. Physical and economic characteristics of farms in Alberta, Saskatchewan and Manitoba, by Great Group.

Soil Great Group	Number of Farms in sample	Physical Characteristics[1]		Crop Distribution[1] (% of cultivated area)						Capital Investment[2]			Income and Expenses[2] ($/ha)					Capital Use Efficiency Ratios[2]	
		Farm size (ha)	Cultivated (% of farmed area)	Summer-fallow	Wheat	Oil-seeds	Oats and Barley	Hay	Im-proved pasture	Total ($/ha)	Machinery %	Livestock %	Total Sales	Operat-ing Expenses	Gross Margin	Fuel	Fert-ilizer	Sales to Invest-ment	Sales to Expenses
Brown Chernozem	5728	547	86.4	41.8	45.0	0.3	5.2	1.9	4.0	1481	16.1	4.5	130.58	42.20	85.40	9.45	0.22	.090	2.98
Dark Brown Chernozem	13423	554	79.6	32.6	37.7	2.0	13.7	5.5	5.5	1650	16.8	6.5	145.90	58.10	84.21	10.86	4.70	.091	2.51
Black Chernozem	41705	339	81.2	22.9	32.4	6.7	20.8	6.4	5.5	2024	17.5	6.0	170.48	78.16	88.51	14.21	10.11	.095	2.22
Dark Gray Chernozem	7237	301	74.5	17.9	21.9	6.5	25.7	16.4	6.8	1514	20.4	10.3	138.56	75.71	60.75	16.50	6.08	.097	1.84
Luvisol	16770	264	70.1	15.9	17.5	4.8	25.4	21.0	10.6	1993	17.8	8.8	127.91	74.50	50.20	16.65	4.77	.077	1.72

[1] Average of polygon means

[2] Average of polygon medians

Table 2.2. Physical and economic characteristics of farms according to soil texture; Alberta, Saskatchewan and Manitoba

		Physical Characteristics[1]		Crop Distribution[1] (% of cultivated area)						Capital Investment[2]			Income and Expenses[2] ($/ha)					Capital Use Efficiency Ratios[2]	
Soil Great Group	Soil Texture	Farm size (ha)	Cultivated (% of farmed area)	Summer-fallow	Wheat	Oil-seeds	Oats and Barley	Hay	Im-proved pasture	Total ($/ha)	Machinery %	Live-stock %	Total Sales	Operat-ing Expenses	Gross Margin	Fuel	Fert-ilizer	Sales to Invest-ment	Sales to Expenses
Brown Chernozemics	Clayey	435	91.1	42.8	46.8	0.5	5.1	0.7	2.5	1672	14.9	3.0	135.20	44.66	87.12	9.37	0.72	.084	2.94
	Loamy	596	84.3	41.3	44.2	0.2	5.2	2.4	4.7	1396	16.6	5.2	128.53	41.10	84.63	9.48	0.00	.093	3.00
	Sandy																		
Dark Brown Chernozemics	Clayey	425	90.5	37.1	44.4	1.8	9.5	2.0	2.8	2029	14.5	2.2	146.63	57.90	88.64	9.76	5.64	.076	2.54
	Loamy	537	79.0	32.3	36.9	2.1	13.8	5.8	5.7	1548	17.5	6.8	143.86	57.35	82.61	11.03	4.54	.095	2.51
	Sandy	822	65.4	27.7	30.5	1.6	19.5	9.4	8.3	1741	16.8	11.4	160.87	65.44	88.48	11.87	5.22	.095	2.47
Black Chernozemics	Clayey	258	89.3	19.4	28.3	6.4	27.5	8.0	5.2	4013	14.8	2.5	185.56	93.08	85.99	15.83	14.94	.066	2.07
	Loamy	356	80.3	25.0	34.4	6.7	18.8	5.5	5.2	1785	17.8	6.2	165.27	72.92	89.23	13.67	8.47	.098	2.29
	Sandy	273	81.3	7.3	18.2	7.1	32.2	12.9	8.4	2184	17.6	7.6	202.24	110.38	84.55	17.41	20.11	.098	1.78
Dark Gray Chernozemics	Clayey	217	83.5	16.5	28.0	6.1	21.2	17.1	5.5	1755	19.7	5.3	140.46	80.22	54.99	17.20	7.76	.086	1.71
	Loamy	343	70.0	18.6	18.8	6.7	28.0	16.1	7.4	1394	20.8	12.7	137.61	72.64	63.63	16.15	5.24	.103	1.90
	Sandy																		
Luvisols	Clayey	269	81.6	17.9	27.4	7.1	19.9	17.0	6.6	1916	18.4	5.5	148.25	78.88	65.24	16.52	8.44	.088	1.87
	Loamy	259	67.8	14.9	14.8	3.7	26.6	22.9	11.9	2070	17.5	9.6	125.19	74.56	47.40	16.92	3.84	.073	1.67
	Sandy	301	74.6	21.4	27.4	10.2	22.0	10.1	5.1	1456	19.6	6.0	124.90	68.52	54.46	14.60	7.87	.092	1.85

The Dark Brown soils had a lower percentage of cultivated land, a higher proportion in oilseeds, oats, barley, improved pasture and hay, and less summerfallow.

The financial picture of farms in the Dark Brown Soil zone was also slightly different from that in the Brown (Fig. 2.2). Total sales per hectare were 10% greater than in the Brown and operating costs were 33% greater (Fig. 2.3) but the gross margin was almost identical at about $84/ha. Farms in the Dark Brown zone had approximately 10% more in capital investment, and it was distributed slightly more to machinery and livestock than in the Brown. The sales/investment ratio was about the same in the Dark Brown soils as in the Brown, but the sales to operating expenses ratio was lower. This was partially due to slightly higher fuel use ($10.86/ha) and much higher fertilizer costs.

Textural differences were more pronounced on the Dark Brown Chernozemic soils than on the Brown. Farm size was dramatically different, with farms on loamy soils being 26% larger and those on sandy soils being 93% larger than farms on clayey soils. Cultivated land also showed considerable variation in that sandy soils were 65% cultivated, loamy soils were 79% cultivated and clayey soils were 90% cultivated. Crop distributions showed clayey soils to have the highest proportion of wheat and summerfallow and the lowest proportion of oats, barley, hay and pasture. Economically, clayey and sandy textured Dark Brown Chernozemics showed marginally better performance than loams, with higher investment levels, total sales and gross margins. The ratio of total sales to operating expenses was consistent for all three textures, but sales to investment efficiency wasconsiderably lower on clayey soils.

Black Chernozemic Soils

The Black Chernozemic soils occupy the largest portion of the productive prairie region, encompassing approximately 198,000 km^2. Farming in this zone is somewhat more varied than in the drier Brown and Dark Brown zones.

The average farm size in the Black Chernozemic zone was considerably smaller than in the Brown and Dark Brown but spring wheat was still the dominant crop. The summerfallow ratio was about one half of that in the Brown zone and two thirds that of the Dark Brown. The proportion of cultivated land in oilseeds, hay, oats and barley wasgreater than in the drier soils to the south.

According to the 1981 census, farms in the Black soil zone showed slightly higher profitability than those of any other soil group. Total sales per hectare were the highest in the region (30% greater than Brown, 17% greater than Dark Brown), and although operating expenses were also higher (85% higher than Brown, 35% higher than Dark Brown), the average gross margin of $89/ha was the highest of all soil types (4% higher than Brown and 5% higher than Dark Brown). Mean total capital investment in the Black soils was greater than either the Brown or Dark Brown and was distributed slightly more to machinery. The sales to investment ratio of .095 was slightly higher than in the other

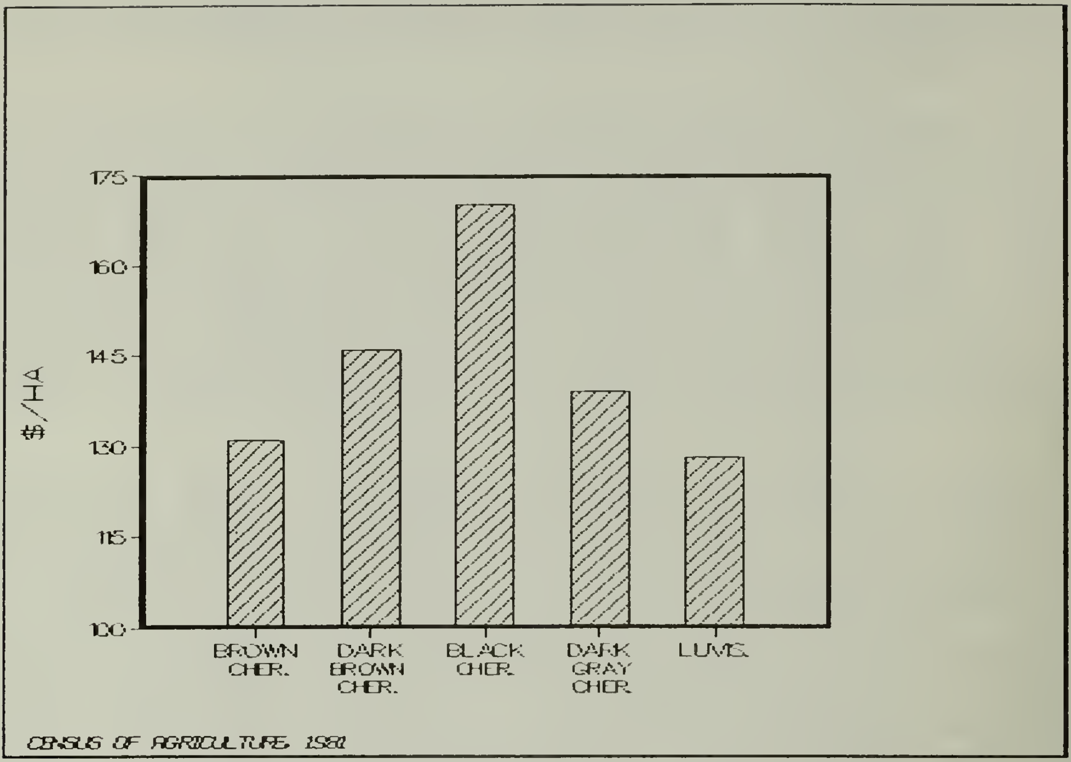


Fig. 2.2 Total sales per hectare by Great Group

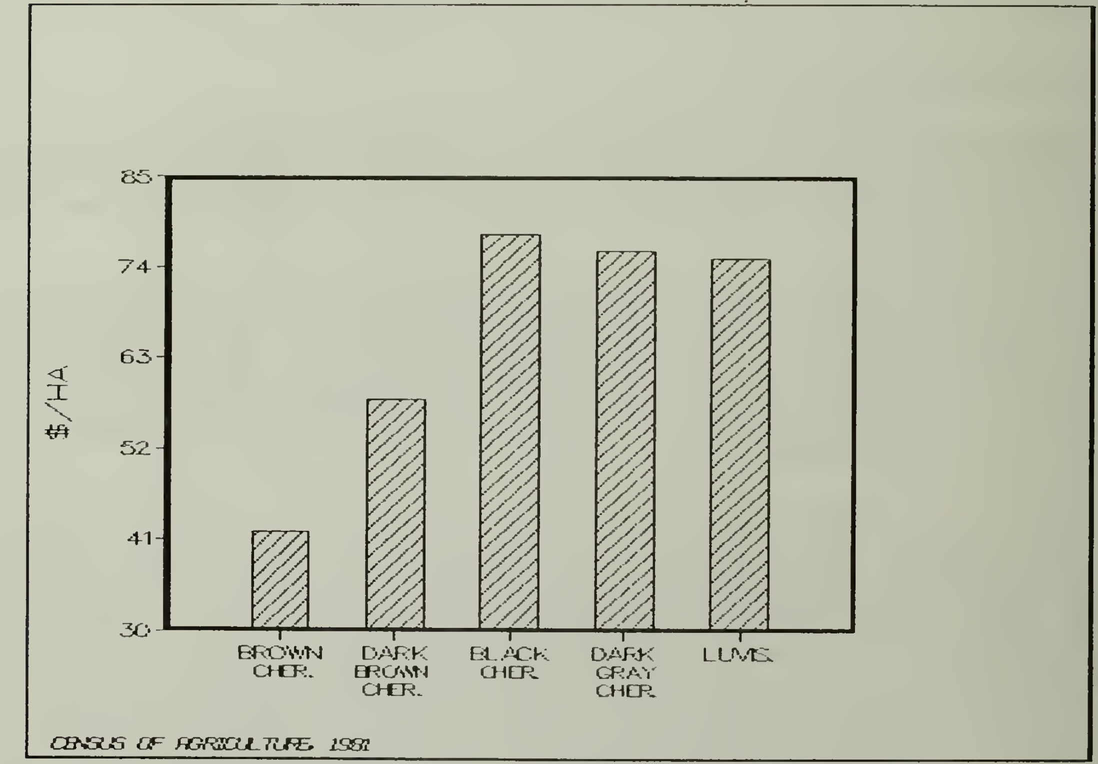


Fig. 2.3 Operating expenses per hectare by Great Group

soil zones and showed good use of investment capital, but the sales to operating expenses ratio of 2.22 showed low returns to expenses (Fig. 2.4). This was probably due to the high operating expenses; fuel use was approximately $14/ha (30-50% greater than that of the Browns and Dark Browns) and fertilizer costs were about $10/ha (twice that in the Dark Brown and many times that in the Brown).

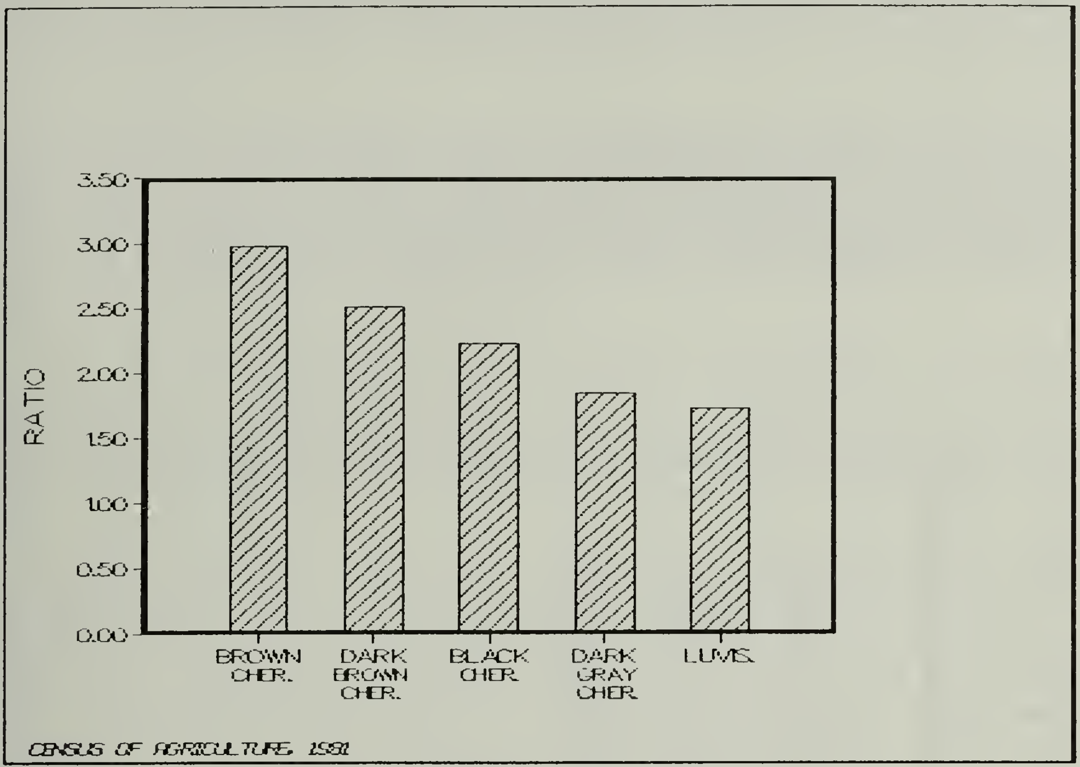


Fig. 2.4 Sales to expenses ratio by Great Group

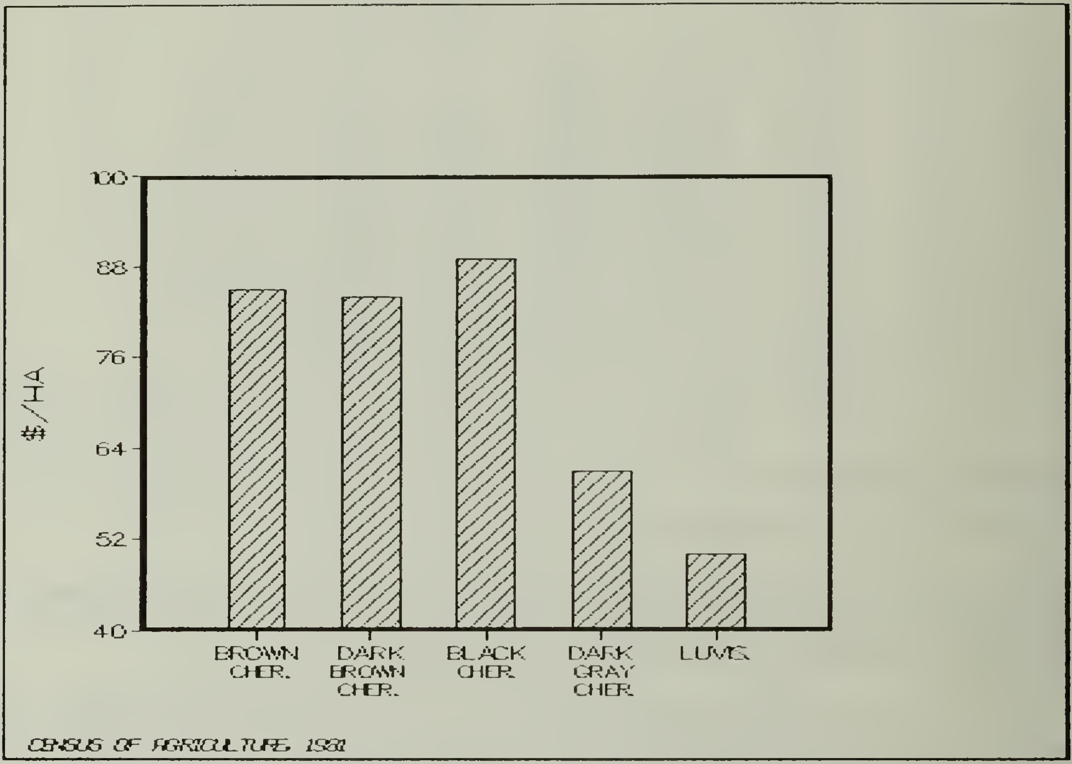
Farms on the loamy textured soils in the Black Chernozemic zone were distinct physically and economically. These farms were considerably larger than those on clayey or sandy textures, the proportion of cropland in summerfallow and wheat was higher and the amount of oats, barley and hay was less. Capital investment per hectare on loamy Black Chernozemics was 44% of that on clays and 82% of sands. Total sales per hectare on loamy soils was less than on clays and sands, but expenses were also less, leaving a higher gross margin and better economic efficiencies. Both fuel and fertilizer use on loamy soils were noticeably lower than on the other textural types.

Dark Gray Chernozemic Soils

The Dark Gray Chernozemic soils occur in an irregular pattern to the north of the Black soil zone and they occupy approximately 42,000 km^2. Farming is generally mixed grain and livestock.

Farm characteristics and cropping patterns in the Dark Gray soils were similar to those of the Black soil zone, except in terms of intensity. Mean farm size (301 ha) was smaller than the Brown, Dark Brown and Black soils, and the proportion cultivated (74.5%) was considerably less. Spring wheat and summerfallow were significant,but coarse grain (oats and barley) was the dominant crop. The oilseed and hay percentages were similar to those of the Black Chernozems. Improved pasture was relatively more widespread than in the Black, Dark Brown or Brown zones.

Although farms in the Dark Gray soil areas had similar cropping patterns to those in the Black zone, their financial performance based on 1981 Census figures was not nearly as good. The mean gross margin of $61/ha was only 69% of that in the Black zone and 72% of that in the Dark Brown and Brown (Fig. 2.5). This resulted from moderate total sales and high operating expenses. Average total capital investment on the Dark Gray soils was $1514/ha, which was distributed more heavily toward machinery and livestock than in any other zone. The relatively low capital value was reflected in the highest sales/investment ratio (.097) of any soil group, but the high level of inputs (for example, fuel $16.50/ha, fertilizer $6.08/ha) resulted in a low sales/operating expenses ratio (1.84). For comparison, it cost $54 in operating expenses to generate $100 in sales on the Dark Gray soils, compared to only $34 on the Brown, $40 on the Dark Brown and $45 on the Black soils.



CENSUS OF AGRICULTURE 1981

Fig. 2.5 Gross margin per hectare by Great Group

There were only two textural types (clayey and loamy) well enough represented to provide meaningful statistics in the Dark Gray Chernozemic soils, but they showed marked differences in characteristics. Farms on clayey soils were considerably smaller, but they had more of their farmland cultivated and more of their cropland in wheat. Summerfallow, coarse grains and improved pasture were less widespread. Farms on clayey soils generally had higher levels of capital investment

(26% greater), higher total sales (2% greater) and higher expenses per hectare (16% greater), but average gross margin was 14% less. The higher cost of farming clay soils is also reflected in the economic efficiency ratios, both of which were lower than for loamy soils.

Luvisolic Soils

The Dark Gray and Orthic Gray Luvisols occur north of the Parkland zone and in the Peace River area. For the purpose of this study, only those polygons which fell in the area of a broad arc to the north and west of the Black Chernozems were analysed. The Luvisolic soils are spatially associated with organic soils, and all farms on either soil type were combined for this analysis.

The cropping pattern on the Luvisols was typical of northern locations, with relatively small farms, a low proportion of farmland cultivated and a high proportion in hay. Oats and barley were the principal cropping choices while wheat and summerfallow were sub dominant. Oilseeds averaged only 4.8% and improved pasture averaged 10.6%.

Farms on Luvisolic soils appeared to be only marginally profitable, as indicated by an average gross margin of only $50/ha in 1980. Average total sales were comparable to the Brown soil groups, but operating expenses were comparatively high. Total capital value was high, and it was generally weighted more to livestock and less to land and buildings than was common in the other soil zones. The sales to investment ratio of .077 was low, as was the sales to expenses ratio of 1.72. Fuel use was the highest of any soil group, but fertilizer costs were moderate.

Textural differences in the Luvisolic soils were the least consistent of any in the study. Although farm size did not vary remarkably, the proportion cultivated ranged from 68% on loams to 75% on sands to 82% on clays. Farms on loamy soils had lower proportions of summerfallow, wheat and oilseeds and higher levels of oats, barley, hay and pasture. Capital investment levels were low on sandy soils while total sales, expenses and gross margins were highest for clays. Fertilizer use on loamy soils was approximately one-half that on sands or clays, and economic efficiencies were the lowest.

DISCUSSION

The crop and land use variables show considerable variation according to soil Great Groups, because these geographical zones reflect broad differences in climatic and landscape conditions particular to crop growth. It appears that the concentration on spring wheat in the southern, drier areas and the reliance on a wider range of crops in the wetter, shorter growing season to the north is a function of the farmer's desire to capitalize on the highest value crop suited to an area, while at the same time substituting more hardy crops to an extent dependent on the risk of crop failure. Factors such as 'farmsize' and 'proportion cultivated' reflect the ease by which technology in the form of large machinery can be successfully substituted for labour. For example, the greater complexity of landscape and amount of native vegetation of cooler and wetter regions reduces the efficiency of large machinery. Also, the reliance on lower valued crops reduces the ablity to amortize purchases of such items.

The economic data reveal that land use intensity varies depending on soil and climate, another environmentally related aspect of farming the Prairies. The variables 'operating expenses', 'capital investment', 'fuel' and 'fertilizer' show that land use intensity (as estimated by the amount of input per unit area) is lowest in the driest Brown soil zone, increases as the moisture increases in the Dark Brown zone, reachs a peak in the Black Chernozemic zone and then drops off slightly in the Dark Gray and Luvisolic zones. This indicates a higher response to inputs in areas of more reliable moisture and higher moisture use efficiency, as well as an attempt by farmers to compensate for smaller farm sizes with greater productivity. The drop in intensity on the Dark Gray and Luvisolic soils is probably a function of the shorter growing season and cooler temperatures.

The economic results of the different strategies of farming are mixed. 'Total sales' and 'gross margin' data show that the high input approach on the Black Chernozems is particularly effective, as both variables reach a peak in that zone. However, when per hectare values are multiplied by farm size, then the larger farms of the Brown and Dark Brown soil zones (at lower intensity) are shown to generate approximately 50% greater gross margins. Farms on Dark Gray and Luvisolic soils are afflicted by high input costs, low productivity and small size; input costs per hectare are comparable to those in the Black zone, sales are only equivalent to those in the Browns and Dark Browns, and farm size is the smallest on the prairies. This results in per farm gross margins only 30% of those of the Brown and Dark Brown zones.

Capital use efficiency ratios are non-unit financial measures that relate to input costs and income without reference to farm size or enterprise type. They measure the effectiveness of a farm operation in turning capital investment and operating dollars into sales dollars.

Sales to capital investment ratios for the study area are generally non-differentiating in terms of the soil zones, with the exception of the Luvisols. In this case the dramatically lower sales to investment ratio reflects both the high investment per hectare common to small farms and diversified enterprises and the low sales common to northern areas.

Sales to operating expenses, however, show a distinctive trend corresponding to soil and climatic regimes. The sales to operating expenses ratios show farms in the Brown Chernozemic zone to be relatively efficient financially, with declining efficiencies in the Dark Brown, Black, Dark Gray and Luvisolic soils. The Dark Gray Chernozems and Luvisols have particularly low conversion efficiencies. It is noteworthy that although the risk of drought is higher in the Brown and Dark Brown soil zones, the financial efficiency of a wheat-fallow rotation in a 'normal' year in these areas is adequate to induce farmers to maintain this practice, rather than adopt more diversified and less risky rotations.

Broad scale variation in the socioeconomic structure of farms can be described according to soil zones, but more specific differences can be determined according to soil texture groups within the zones. Generally, sandy soils tend to support larger, less intensive farms (more hay and pasture). This is consistent with the lower productivity that would be expected on such soils, due to lower fertility and moisture holding capacity. The lower values for summerfallow in most sandy soils may represent a situation in which summerfallowing is only moderately effective in creating a reserve of soil moisture. Loamy soils tend to range between sands and clays for variables reflecting production intensity. The higher fertility levels and better moisture storage characteristics of clay soils combine to create a situation of smaller, more intensive and more productive farms.

The economic relationship between farms on clayey and loamy soils is generally consistent with land use intensity, with farms on clayey soils showing higher total sales, higher expenses and higher gross margins. However, in the Dark Brown and Black Chernozemic zones, farms on sandy soils have higher per hectare sales and expenses, and roughly equivalent gross margins to those on clayey soils. It was not clear whether this was due to a higher livestock component or to other factors. The fact that sales to capital investment ratios were generally lower for clay soils indicates that farms on these soils either require relatively greater investments, or that they are over capitalized. Generally higher sales to operating expenses ratios on loamy and clayey soils reflects a higher response to inputs on these soils.

This study was undertaken to evaluate relationships between regional soil-climatic regimes and farm socioeconomic characteristics and management strategies. The 1:5 million scale of the study limited the degree to which features such as cropping systems and enterprise types could be considered in the analysis, but the reliance on Census of Agriculture data provided sample sizes adequate for sound statistical interpretations. At the same time, the generalization inherent in the Soils of Canada map deemed that relationships between farm characteristics and soil types must be interpreted somewhat indefinitely.

The data indicate that over the history of agriculture on the Canadian prairies, a great deal of adjustment of economic and cropping strategies to soil and climatic conditions has been undertaken. This adjustment is in some cases related to biological feasibility (crop suitability) and in some cases to risk management. Whatever the cause, these differences should be recognized in developing and administering effective and equitable farm programs. In light of these data it would be inconceivable to consider that technology transfer programs for example, would be equally beneficial to producers in the Brown Chernozemic and Dark Gray Chernozemic soil zones.

In addition to the information regarding socioeconomic - physical resources relationships, a methodology appropriate for small scale socioeconomic evaluation of pre-defined land units is presented. This methodology makes use of Census of Agriculture data, a largely unexploited source of widespread and uniform farm data. With some modifications this procedure could very readily serve in time-series land evaluation efforts.

The shortcomings of this study, in particular lack of detail, indicate the need for further investigations. More detailed resource maps, several Census dates, differentiation on the basis of enterprise types or cropping systems, a greater range of variables and more exhaustive statistical procedures could be employed to advantage in future studies of this type.

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CLIMATIC RISK ANALYSES OF THE PRAIRIE REGION

A. Bootsma and R. de Jong

INTRODUCTION

Knowledge of the soil-climate resource base under which agriculture functions is fundamental to the development of agricultural infrastructures, support policies and for deriving solutions to problems. Recent successive droughts have re-emphasized the dependency of agriculture on the weather, and on the interaction of soil moisture with crop yields. Soil and climatic resources still control the production potential of crops and the types of management and conservation practices that optimize production, in spite of the tremendous technological achievements that have been gained. In the short term, it is the year to year fluctuations in weather that contribute to changing production levels, aggravate price and market stabilization problems, increase economic disparity for farmers and influence the need for government assistance to farmers in financial distress.

The importance of soil water in the prairie region is readily apparent when reviewing the agricultural system. Dryland crop production is directly related to the soil water regime, and any attempt to estimate crop yields must include soil water effects.

The seasonal distribution of water within the soil profile is a complex interaction of many variables related to current and past occurences of weather, crops, soils and agricultural management practices. Simulation models, varying from elaborate physically based models to rather simple water budgets, have been developed to describe the fate of water in the soil-plant-atmosphere continuum. In the physically based models, water movement in and through the soil is simulated in accordance to the soil water flow equation. These models are process oriented, distinguishing between transpiration, soil evaporation and free water evaporation, and use parameters which can be assigned physical meaning. However they require a complete physical characterization of the soil profile in terms of water retention and hydraulic conductivity functions. Moreover, these models use relatively small depth and time increments which consequently might give rise to excessive computer time requirements.

The water budget models operate by solving a simple water balance equation, in which precipitation is input, and actual evapotranspiration is calculated in terms of potential evapotranspiration reduced according to the prevailing soil water conditions by 'root' coefficients. The assumptions are that (i) there is no drainage when the water content of the profile is below a reference water content value termed field capacity (ii) no extraction of water occurs when the soil dries below the permanent wilting point and (iii) the water content of the soil, if exceeding field capacity, will return to field capacity after one day. The available water-holding capacity (AWC) of the soil, defined as the difference in water content between field capacity and permanent wilting point, is a required input. The water budget models operate on a timescale of one day, and are therefore relatively inexpensive to run on a computer.

Climatic water budget models have been used to calculate soil water deficits and moisture indices for various locations on the Prairies (Sly and Coligado 1974; Sly 1982; De Jong et al. 1984; Shields and Sly 1984). In attempts to reduce variability, seeding and harvest dates were assumed to remain constant from one year to the next for all locations. The models used standard time periods of 30 years, and they excluded the extreme dry years of the 1930's. Yet, the variability of the data was large. For example, at Regina the mid-season estimated soil water reserves for wheat grown on a clay soil ranged from 52 mm in 1958 to 176 mm in 1942. The mean for the 1941 to 1970 period was 113 mm, with a coefficient of variation of 31%. This temporal climatic variability has considerable effect on annual production and farmers' income, and it is a major factor in risk management decisions in the region.

Assessments of temporal climatic variability based on 30-year periods or less can result in biased results. For example, studies have shown that the weather in central North America has been less variable during the 1960's and early 1970's than in some previous decades (Thompson 1985; Robertson 1974). A more recent investigation suggests that increased weather stability continued into the late 1970's on the Canadian prairies (Stewart et al. 1986). It is quite probable that climatic conditions during the next decade will be more variable (and also more normal) than the past few decades. Use of a 60-year period which includes the drought years in the 1930's therefore seemed to be appropriate in analyzing variability.

While the extremes in climatic variability influence the limits of agricultural production, the probabilities of various climatic events provide a sound basis for the development of viable strategies for risk management. Determination of these probabilities can directly aid farmers and other decision makers with regard to various aspects of agriculture.

The objective of this study was to evaluate seasonal and spatial distributions of soil water reserves and water stress indices for crop production on the Prairies. Spring wheat, grown in a wheat-fallow rotation and in a continuous wheat system were examined, as well as perennial forage "aridity" indices. Probability analyses of soil water reserves and stress indices were also developed.

Soil Available Water-holding Capacity (AWC)

Soil available water-holding capacity (AWC) is an important determinant of the agricultural soil capability in areas of dryland agriculture (Shields and Ferguson 1975). Information on this soil parameter is needed for the geographical interpretation of soil water and crop modelling results, as well as for land evaluation purposes. However, field measurements of AWC's are not available for large geographical areas.

Shields and Sly (1984) and De Jong et al. (1984) presented data which show that soil textural classes can be equated to AWC classes as shown in Table 3.1. The absence of organic matter in this general relationship is due to the fact that it contributes relatively little to available water in the soil profile because (i) an increased organic matter content raises both the lower and the upper limit of available water and (ii) organic matter is only of importance in the A horizon, which represents only a small proportion of a 120 cm deep profile. For example, when using the equations developed by

Table 3.1. Relationship between available water-holding capacity and soil texture.

Class	Available Water-holding Capacity (mm)	Textural Group
1	50	Sand; loamy sand
2	100	Sandy loam; gravelly loam
3	150	Very fine sandy loam; loam; gravelly silt loam
4	200	Silt loam; sandy clay loam; clay loam
5	250	Silty clay loam; sandy clay; silty clay; clay; heavy clay
6	-	Solonetzic soils
7	-	Organic soils; Organic Cryosols; soils with a shallow water table
R	-	Rock outcrop

De Jong and Loebel (1982) one can calculate that with an increase in organic carbon content from 1% to 6% and with doubling the A horizon from 10 cm to 20 cm, the AWC of the A horizon increases by only 12 mm and 16 mm respectively for a sandy loam and a clay.

Generalized Soil Landscape Maps (GSLM's) of the three Prairie provinces, except northern Saskatchewan, are available in digitized form at a scale of 1:1 million (Shields et al. 1987). Textural classes of soil parent material occupying the dominant part of map polygons are included as part of this computerized information base. AWC maps were derived from the GSLM's by substituting AWC classes for parent material textural groups (Table 3.1) and by assuming that there were no lithological discontinuities.

Areas dominated by Solonetzic soils were assigned class 6 in accordance with conventions adapted for the GSLM's. AWC data for these soils is unreliable due to the influence of their saline and/or alkaline subsoils. Water in Solonetzic soils may not be available to the crop because of low osmotic potentials, a factor not accounted for in the present concept of available water.

Polygons with a high water table were assigned class 7 and excluded from further analysis because capillary rise of water from a water table invalidates the concept of available water as used herein. Outcrops of rock were assigned class R.

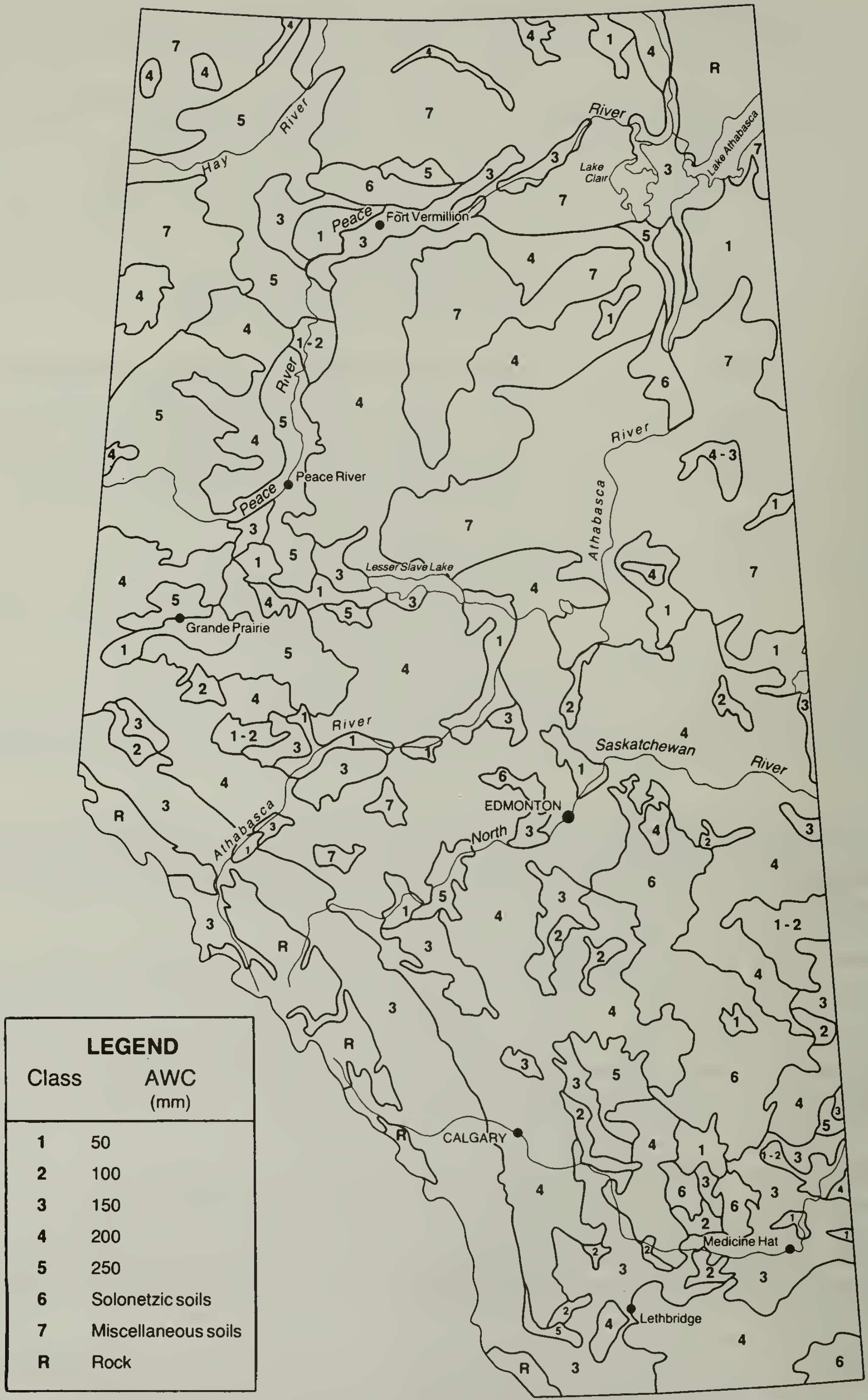


Fig. 3.1a. Classes for available water-holding capacity (AWC) for Alberta (for legend see Table 3.1).

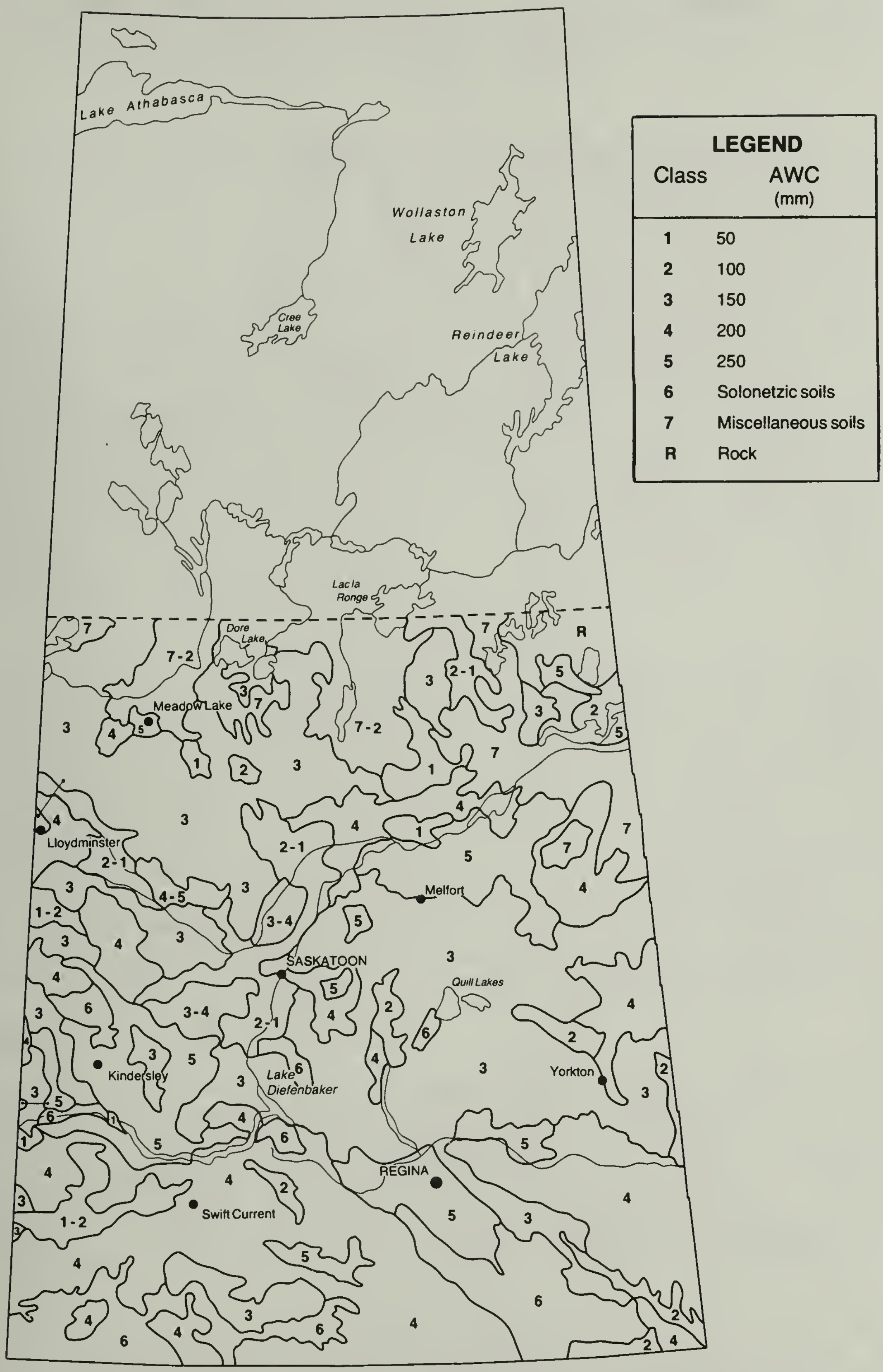


Fig. 3.1b. Classes for available water-holding capacity (AWC) for Saskatchewan (for legend see Table 3.1).

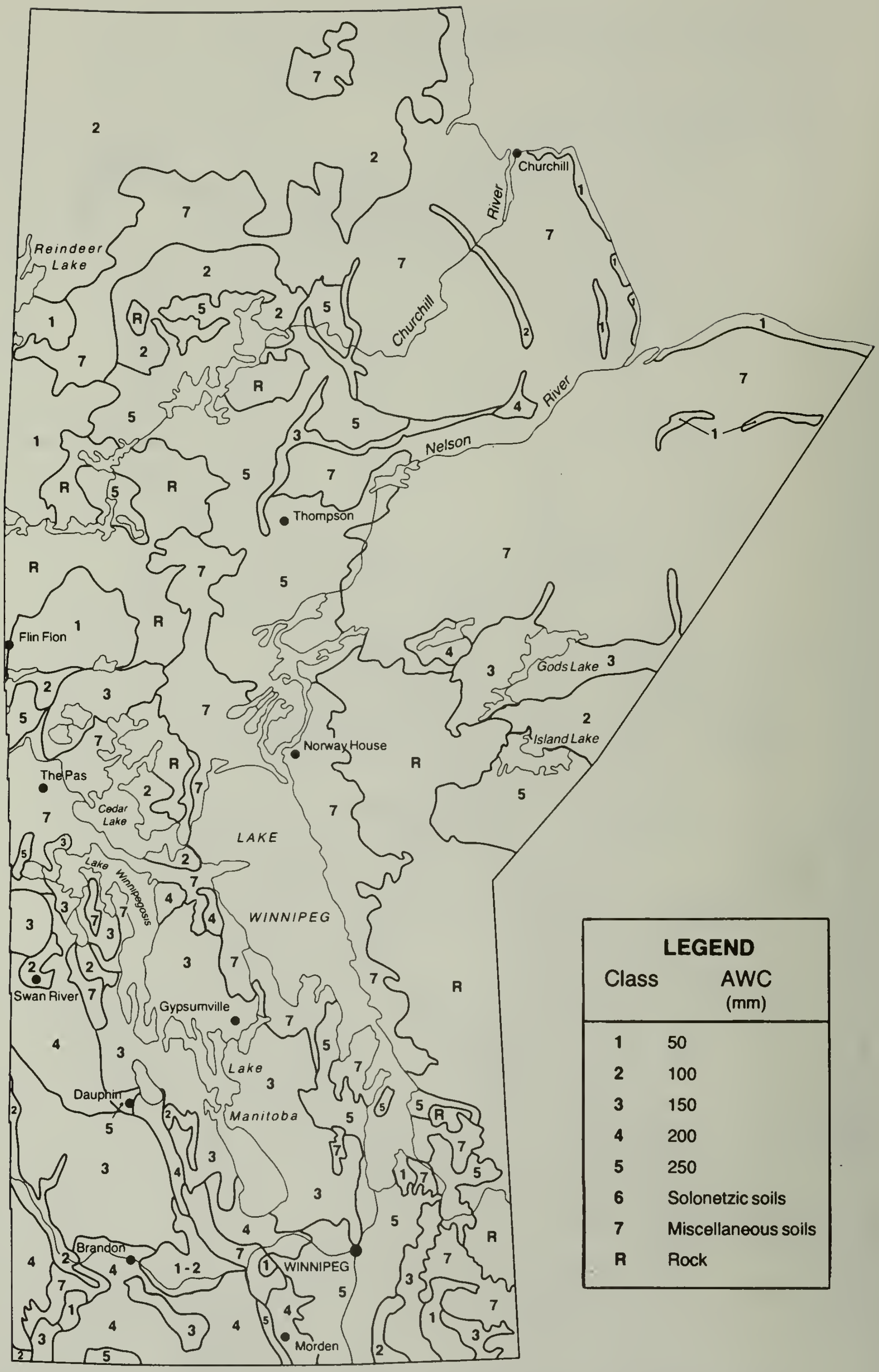


Fig. 3.1c. Classes for available water-holding capacity (AWC) for Manitoba (for legend see Table 3.1).

To improve the readability of the AWC maps, they were simplified by eliminating small areas and by combining soils which had an AWC of 50 and 100 mm. For display purposes the maps were then reduced photo-mechanically to a scale of 1:5 million (Fig. 3.1a, 3.1b and 3.1c).

Laboratory methods used to determine the upper and lower limits of available water (respectively at -33 kPa and -1500 kPa matric potential) have been criticized (Ritchie 1981; Ratliff et al. 1983) and new approaches based on field measurements are emerging (Cassel et al. 1983; McKeague 1987). But despite the criticisms, the concept of available water as estimated from laboratory data and predictive equations based on limited empirical data is still a practical necessity because a large data base of field measurements is lacking for Canadian soils. Moreover, it was found that the general relationship between texture and AWC (Table 3.1) compared reasonably well with some in-situ measurements from Manitoba (Table 3.2), especially for the finer textured soils. Most of the coarser textured soils in the Manitoba study were located in areas affected by a high water table as indicated on the GSLM and hence their measured AWC is suspected to be influenced by the capillary fringe region. When these soils are excluded from the comparison, only four soils differ in excess of 20% between measured and estimated AWC. Other factors, like soil structure, organic matter content and bulk density, might be of more significance in their contribution to available water in these coarser textured soils. The presence or absence of very fine sand in coarse textured soil is also of importance (McKeague 1987).

Agricultural land (Fig. 3.2) is restricted to the southern half of the Prairie provinces, with the exception of the Peace River and Fort Vermillion areas where clearing of forest is an ongoing activity. A small proportion of land farmed in Manitoba (Fig. 3.1c) is affected by high water tables. Solonetzic soils, for which no AWC's were estimated, are found primarily in Alberta (Fig. 3.1a) and to a lesser extent in Saskatchewan (Fig. 3.1b) and Manitoba (Fig. 3.1c). Within the agricultural region small and scattered polygons have an AWC of 50 and 100 mm. It is of interest to note that in the most arid region of the Prairies (the Brown soil zone), a large proportion of these low AWC soils are under grassland. The vast majority of the polygons were assigned an AWC of 150 or 200 mm. Relatively large areas with a high water-holding capacity (250 mm) are found in the Peace River district, around Kindersley, Melfort and Regina in Saskatchewan and around Winnipeg.

Climatic Water Budgeting Procedures

Analyses of soil water reserves and water stress indices require daily estimates of soil water content. In previous studies, Sly (1982) used the Versatile Soil Moisture Budget, VSMB (Baier et al. 1972, 1979) to estimate long-term averages of soil water reserves for spring wheat. Modifications to these procedures were introduced in this study in an attempt to account for temporal and spatial variations in seeding and phenological dates by (i) estimating seeding dates from weather and soil conditions and (ii) incorporating a biometeorological time scale (Robertson 1968) into the VSMB.

Daily maximum and minimum air temperatures and daily precipitation data as reported by Environment Canada (Atmospheric Environment Service) and daily solar radiation at the top of the atmosphere were used in the climatic water budget calculations. These data were available from computer files maintained by the Agrometeorology section of the Land Resource Research Centre. Data for

Table 3.2. In situ and estimated soil water-holding capacities of selected Manitoba soils (personal communication Dr. W. Michalyna, Canada-Manitoba Soil Survey)

Series name	Texture	AWC (mm)	
		Measured	Estimate
Willowcrest	loamy sand	191	W*
Longplain	sand	135	W
Almasippi	sand	188	W
Reinland	sandy loam	210	W
Lakeland	silty clay	210	250
Lakeland	silty clay loam	232	250
Swanford	sandy clay loam	211	200
Durban	sandy loam	201	100
Durban	sandy loam	165	100
Kenville	clay loam	223	200
Kenville	silty clay	256	250
Black Lake	silty clay	290	250
Paulson	clay	283	250
Minitonas	clay loam	216	200
Bearford	clay loam	247	S
Pelan	clay	250	250
Scanterby	clay	282	250
Dezwood	clay loam	168	200
Hebbot	clay loam	254	250
Poyser	clay loam	209	200
Darlingford	clay loam	192	200
Darlingford	clay loam	209	200
Newdale	clay loam	242	200
Newdale	clay loam	217	200
Erickson	clay loam	210	200
Erickson	loam	222	150
Libau	clay	229	250
Inwood	loam	191	150
Beaverdam	sandy loam	117	100
Ladywood	loamy sand	214	W
Plumridge	sandy loam	214	W
Plumridge	sand	104	W
St. Malo	very fine sandy loam	186	150
Aneda	loam	147	150
Halicz	clay loam	230	200

* W - located in high water table area
S - Solonetzic soil

Table 3.3. Climatic stations with period of observation

Alberta	
Beaverlodge CDA	1925-1984
Lacombe CDA	25- 84
Lethbridge CDA	25- 84
Medicine Hat A	25- 84
Olds	25- 84
Ranfurly	25- 84
Manyberries CDA	29- 84
Hanna	32- 78
Brooks AHRC	42- 84

Manitoba	
Birtle	25- 84
Brandon CDA	25- 84
Morden CDA	25- 84
Waskada	25- 84
Winnipeg A	25- 84

Saskatchewan	
Indian Head CDA	1925-1984
Regina A	25- 84
Melfort CDA	25- 84
Prince Albert A	25- 84
Saskatoon A	25- 84
Scott CDA	25- 84
Swift Current A	25- 84
Tugaske	25- 84
Aneroid	42- 84
Val Marie	42- 84
Kindersley KY	42- 84
Yorkton A	42- 84
Midale	42- 84

the period 1925-1984 for 19 stations were used. These were supplemented by data from 8 stations, located primarily in the driest part of the Prairies, with records ranging from 58 to 43 years within the same period. All stations along with the period of observation are listed in Table 3.3, and their approximate locations are shown in Fig. 3.2 in relation to major soil groups on the prairies.

The VSMB balances water gained from precipitation less runoff and deep percolation with water lost by evapotranspiration from the rooting zone of the crop. The net loss or gain each day is added to the water already in the root zone. Water is withdrawn simultaneously, but at different rates, from different depths in the soil profile in relation to the rate of potential evapotranspiration calculated from the air temperature and solar radiation (Baier and Robertson 1965; Baier 1971), the stage of crop development, water release characteristic of the soil and available soil water content.

The assumed rooting depth of 120 cm was divided into six standard zones, and the AWC of each zone was calculated as a percentage of the total (Baier et al. 1979). Four AWC's were used (100, 150, 200 and 250 mm) to represent the AWC's of various soil textural groups (Table 3.1).

An estimate of seeding dates was esssential to facilitate an accurate representation of crop growth and development during a specific year. Whereas previous studies tended to use an average date to indicate the start of the growing season, usually chosen as May 1 or May 20 (Sly, 1982), in this study the seeding date was estimated from prevailing daily weather and soil conditions. It was assumed that a crop was seeded when the five criteria in Table 3.4 were met simulataneously for ten days, starting April 15. These

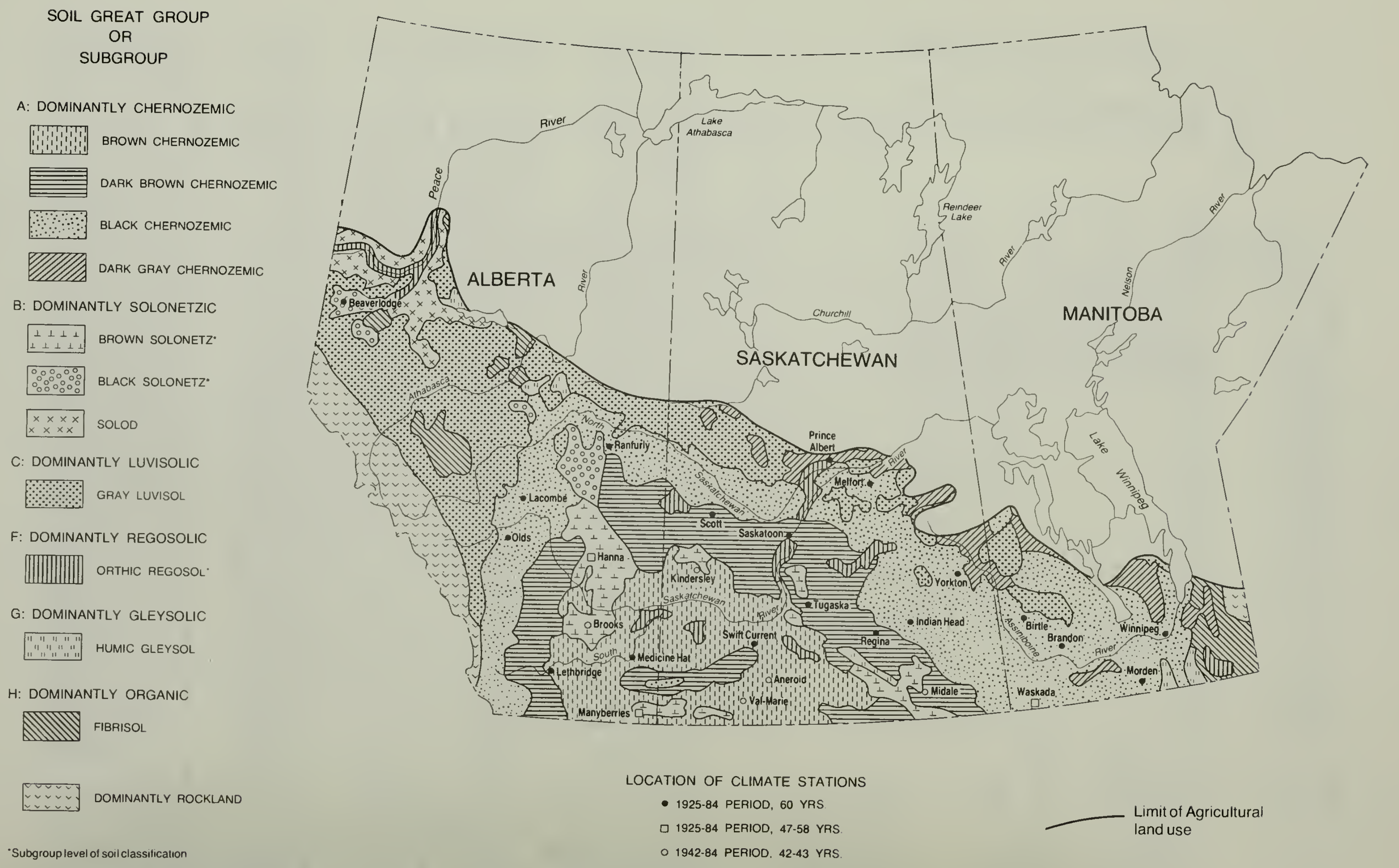


Fig. 3.2. Location of climate stations and periods of record in relation to major soil groups.

Table 3.4. Criteria used to estimate seeding dates

Variable*	Criteria†
3/4 TMAX + 1/4 TMIN	>7°C
Daily precipitation	<2 mm
Snow on ground	<10 mm
SW_1	$<0.90\ AWC_1$
SW_2	$<0.95\ AWC_2$

* TMAX and TMIN - daily maximum and minimum air temperature; SW and AWC - available soil water and available water-holding capacity; The subscripts 1 and 2 refer to zone 1 and zone 2.

† Seeding was assumed not to start until after 10 days with these conditions have occurred after April 15.

criteria were selected by analyzing 22-33 years of data from seventeen climate stations, chosen to represent 13 crop districts selected for seeding date tests. The VSMB was used to compute daily soil moisture contents from April through June. Initial moisture contents on April 1 in each individual year were obtained from Sly (1982). Bare soil was assumed for the entire spring period. Various soil moisture, precipitation and temperature criteria were used to generate estimates of seeding dates for the predominant soil textural group in each crop district. Soil moisture thresholds ranging from <0.80 AWC to <0.98 AWC for the top two zones were tried, based on results of previous field work-day studies reported in the literature (Baier et al. 1978; Rutledge and McHardy 1968; Selirio and Brown 1972). The best seeding date criteria were selected by comparing observed seeding dates (Statistics Canada, crop reporting files) with model estimates using linear correlation analysis.

Results of the best seeding date criteria tested are presented in Table 3.5. Correlation coefficients between estimated and observed dates ranged from 0.35 to 0.79. Biases in the mean values were less than 2 days for the crop districts in Saskatchewan and Manitoba, but up to 7 days for Alberta. Standard errors were usually less than 1 week. Differences between estimated and observed dates may, in part, be due to the fact that one climate station or one AWC does not adequately represent a whole crop district. Some subjectivity in the observed data is also suspected. Overall, estimates were considered sufficiently accurate for a study of this nature. The seeding date criteria used in this study (Table 3.4) were a slight modification of the ones for which test results are presented. Although comparisons using the final criteria are not available, similar or slightly improved accuracies may be expected.

The rate of water uptake by the roots was simulated by crop coefficients which changed as the crop went through five phenological stages: seeding to

Table 3.5. Comparisons between estimated and observed seeding dates for selected crop districts and climate stations.

Crop District	Predominant soil AWC (mm)	Climate Station	Test Period	Average seeding date Estimated	Observed*	r**	SEE† (Days)
Alberta (A.R.A.)††							
2	200	Taber	1956-84	May 6	May 13	0.35	5.6
2	200	Gleichen	"	May 8	May 13	0.57	4.9
2	200	Three Hills	1956-77	May 8	May 14	0.61	3.7
4a	200	Hughenden	1956-84	May 11	May 14	0.42	3.7
6	200	Campsie	"	May 7	May 15	0.69	3.8
7	250	Beaverlodge CDA	"	May 19	May 13	0.64	3.6
Saskatchewan							
1b	150	Broadview	1952-84	May 14	May 15	0.45	7.0
2b	250	Regina CDA	"	May 14	May 12	0.79	5.0
3bn	200	Swift Current A	"	May 10	May 10	0.50	5.1
4a	200	Consul CDA EPF	"	May 6	May 5	0.61	6.0
7a	150	Scott CDA	"	May 10	May 10	0.60	4.6
8a	250	Porcupine Plain	"	May 20	May 19	0.51	5.4
8a	250	Nipawin 2	"	May 17	May 18	0.65	5.5
Manitoba							
1	150	De Loraine	1954-84	May 12	May 13	0.51	7.6
3	200	Morden CDA	1952-84	May 14	May 14	0.46	9.5
3	200	Portage La Prairie A	"	May 15	May 14	0.69	7.8
11	200	Dauphin	"	May 16	May 16	0.59	6.4

* Source: Crops Section, Agricultural Statistics Division, Statistics Canada, Ottawa

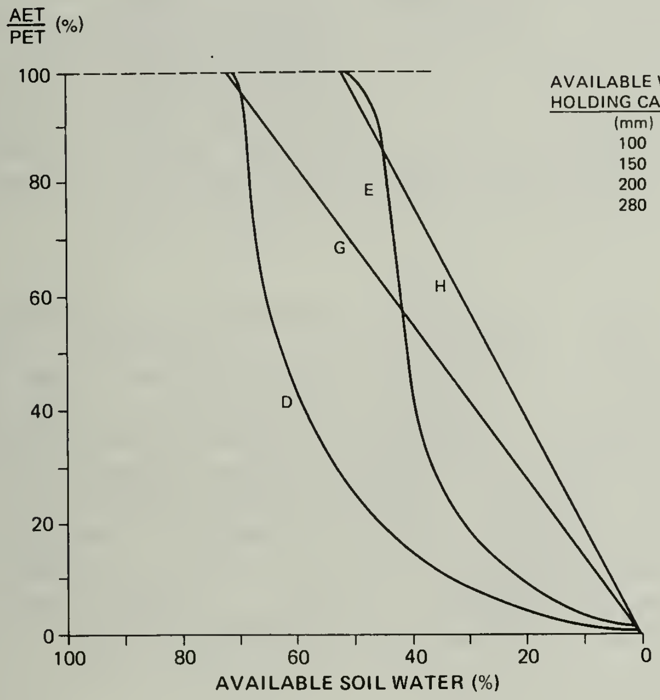
** Correlation coefficient

† Standard error of estimate based on linear regression

†† Agricultural Reporting Areas

crop emergence, jointing, heading, soft dough and ripe (= harvest). The length of these growth stages were defined by a biometeorological time scale (Robertson 1968), which required daily air temperature and photo-period data. The latter were calculated from the station's latitude using astronomical equations (Robertson and Russelo 1968). Soil water conditions were assumed not to have significant influence on phenological development, and therefore were not taken into consideration (Davidson and Campbell 1983).

Different soil water characteristic curves were taken into account by utilizing several typical water release (or Z) curves (Baier and Robertson 1966). Comparisons with limited soil water measurements indicated that in applying the VSMB over an area as large as the Prairie region, the combinations of Z curves, cropping practices and soils shown in Fig. 3.3 gave the most realistic soil water estimates (Sly 1982).



AVAILABLE WATER - HOLDING CAPACITY (mm)	Z CURVE	
	CROP	FALLOW
100	H	E
150	H	E
200	G	D
280	G	D

Fig. 3.3. Relationship between the ratio actual:potential evapotranspiration (AET/PET) and available soil water for different AWC's (after Sly 1982).

The snow budgeting procedure, described by Baier et al. (1972), was used during the winter period and provided an estimate of soil water reserves in spring; it also permitted the computer program to run continuously for the number of years for which data were available.

Assuming a crop-fallow rotation meant that a single computer run using climatic data for the 1925-1984 period provided only 30 years of soil water data under wheat and 30 years under summerfallow. An additional 30 years of data for both the crop year and the fallow year were obtained by restarting the second run with a fallow year, if the first run started with a crop year. In this way a total of 60 years of data were generated for both the crop and the fallow year. In the continuous crop rotation a single computer run over 60 years was sufficient.

Soil water contents were not available at the beginning of the period under study. The computer program started with an assumed water content of 50% of the maximum possible in each zone on April 15 of the year prior to the first one used. Although this assumption is not valid in both the driest and wettest regions of the prairies, the effect on soil moisture estimates in the spring of the following year will be relatively small.

Probability Analyses of Derived Variables

Probability analyses for each station and for each of the four AWC's were carried out for 34 selected variables calculated in this study (Table 3.6), according to procedures described by Spiegel (1961). The 60 year data of each variable were arbitrarily grouped into 16 classes with varying class interval sizes. Relative cumulative frequency distributions were calculated for each class and fixed probability levels at 10, 25, 50, 75 and 90% were calculated for each variable by linear interpolation (see eg. Fig. 3.4). Probabilities that the value of the variable was less than selected criteria (Table 3.7) were calculated in a similar way. Appendix 3.1 illustrates the type of summary tables that were generated for each variable.

Soil Water Content at Seeding

Daily estimates of soil water reserves at seeding for continuous wheat and wheat-fallow rotations were subjected to the probability analyses described in the previous section. Presentation of data was simplified by using zonation maps to display the spatial distribution of the derived variables. The soil water content at seeding for wheat-fallow rotation for the 150 mm AWC, 50% probability level was selected as the "standard" variable for mapping. Since the network of 27 climate stations used in this study (Fig. 3.2) was too sparse to construct accurate zonation maps, previous results by Sly (1982) using 1941-70 and 1950-79 data were used to increase station density (Fig. 3.5). Sly's water contents for May 1 seeding were highly correlated with the water contents calculated in this study for the 27 stations (Fig. 3.6).

The following regression equation fitted to the data was used to adjust Sly's values to the 1925-84 period used in this study:

$$Y = -462.9 - 2.9174\ X + 85.220\ (X)^{1/2} \qquad R^2 = 0.96 \quad SE = 6.3\ \text{mm}$$

where Y is the soil water content for the 1925-84 period, and X is Sly's data for the 1941-70 and 1950-79 periods (150 mm AWC, 50% probability). Geographic patterns in the residual values from this regression were used to make minor adjustments to the regression estimates when appropriate. Soil water content at seeding (150 mm AWC, 50% probability) was plotted on 1:5 million scale maps and zone lines were drawn at class intervals of 15 mm of water, resulting in eight zones with water contents ranging from $\geq$ 140 mm in zone S1 to $\leq$ 50 mm in zone S8 (Fig. 3.7, Table 3.8). Assuming a water use efficiency (WUE) of 80 kg grain/ha/cm for spring wheat (De Jong and Cameron 1980), average yield increments of 120 kg/ha can be expected between adjacent zones for fallow seeding on soils with 150 mm AWC in those areas where production is limited by

Table 3.6. List of variables which were subjected to probability analyses.

Variable No.	Variable
1	seeding date, continuous wheat (Julian day)
2	emergence date, " " "
3	heading date, " " "
4	soft dough date, " " "
5	harvest date, " " "
6	harvest date, continuous barley
7	first fall frost below 0°C (Julian day)
8	" " " -2°C "
9	seeding date, wheat after fallow (Julian day)
10	emergence date, " "
11	heading date, " "
12	soft dough date, " "
13	harvest date, " "
14	harvest date, barley after fallow "
15*	"seeding date", wheat in fallow year "
16	days between first 0°C and harvest, continuous wheat
17	" 0°C " " barley
18	" -2°C " " wheat
19	" -2°C " " barley
20	" 0°C " wheat after fallow
21	" 0°C " barley "
22	" -2°C " wheat "
23	" -2°C " barley "
24	total water content at seeding, continuous wheat (mm)
25	" heading, "
26	" seeding, wheat after fallow (mm)
27	" heading, "
28*	" "seeding", wheat in the fallow year (mm)
29	accumulated stress, seeding to harvest, continuous wheat
30	" jointing to soft dough, "
31	" seeding to harvest, wheat after fallow
32	" jointing to soft dough, "
33	water deficit - wheat (mm)
34	water deficit - forage (mm)

* Although wheat is not seeded in the fallow year, for the purpose of this study a seeding date is estimated based on the soil water content in the spring of the fallow year.

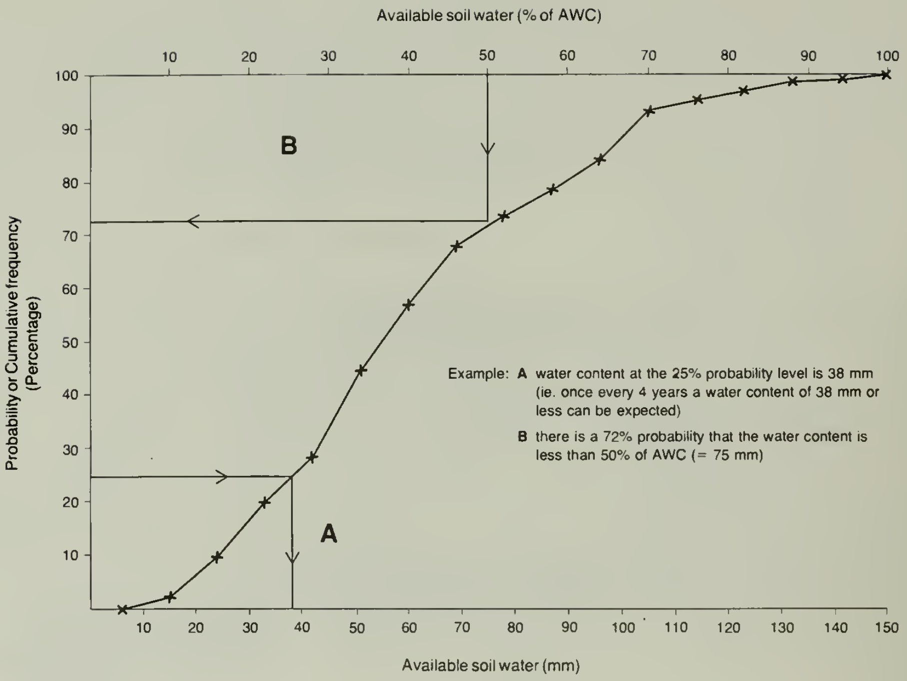


Fig. 3.4. Probability analysis of soil water content at seeding date (fallow-wheat rotation) at Medicine Hat A, 150 mm AWC.

Table 3.7. Criteria for "probabilities that the value of variable is less than"

Variable	Criteria
Thermal resources (days)	-20, -10, 0, 10, 20, 40, 60
Soil water content (% of AWC)	90, 75, 50, 25, 10
Water stress indices	0, 10, 20, 30, 40
Water deficit - wheat (mm)	50, 150, 250, 350, 450
Water deficit - forage (mm)	150, 250, 350, 450, 550

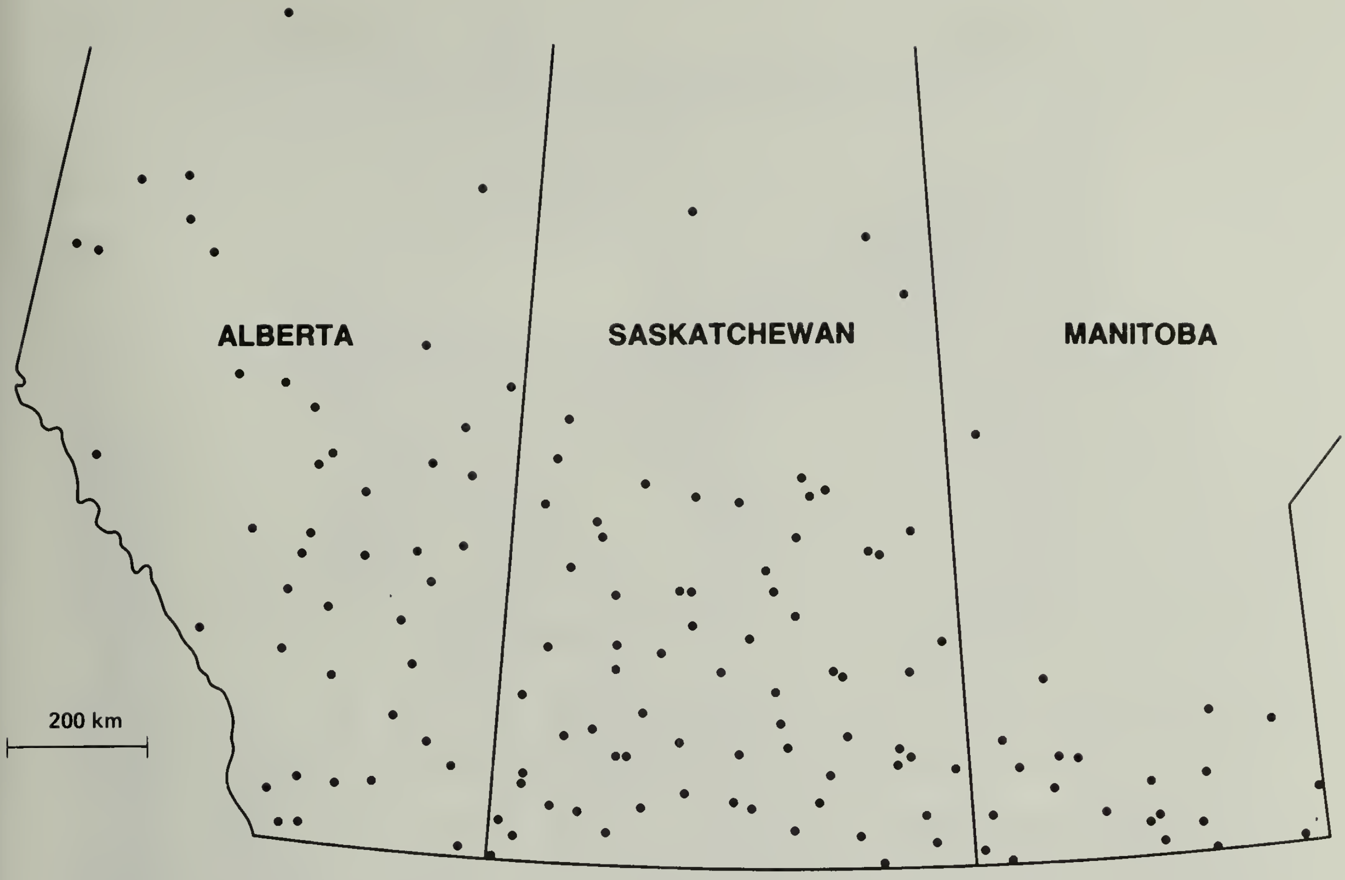


Fig. 3.5. Distribution of available climate stations when data from 1941-70 and 1950-79 periods are included.

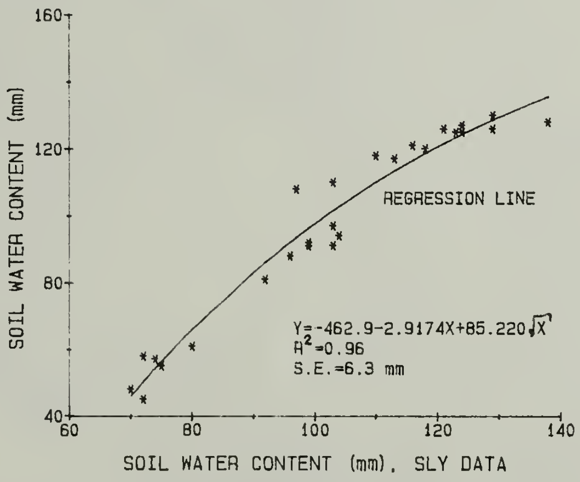


Fig. 3.6. Comparison between soil moisture at seeding as estimated in this project with Sly data for May 1 seeding (wheat-fallow rotation, 150 mm AWC, 50% probability).

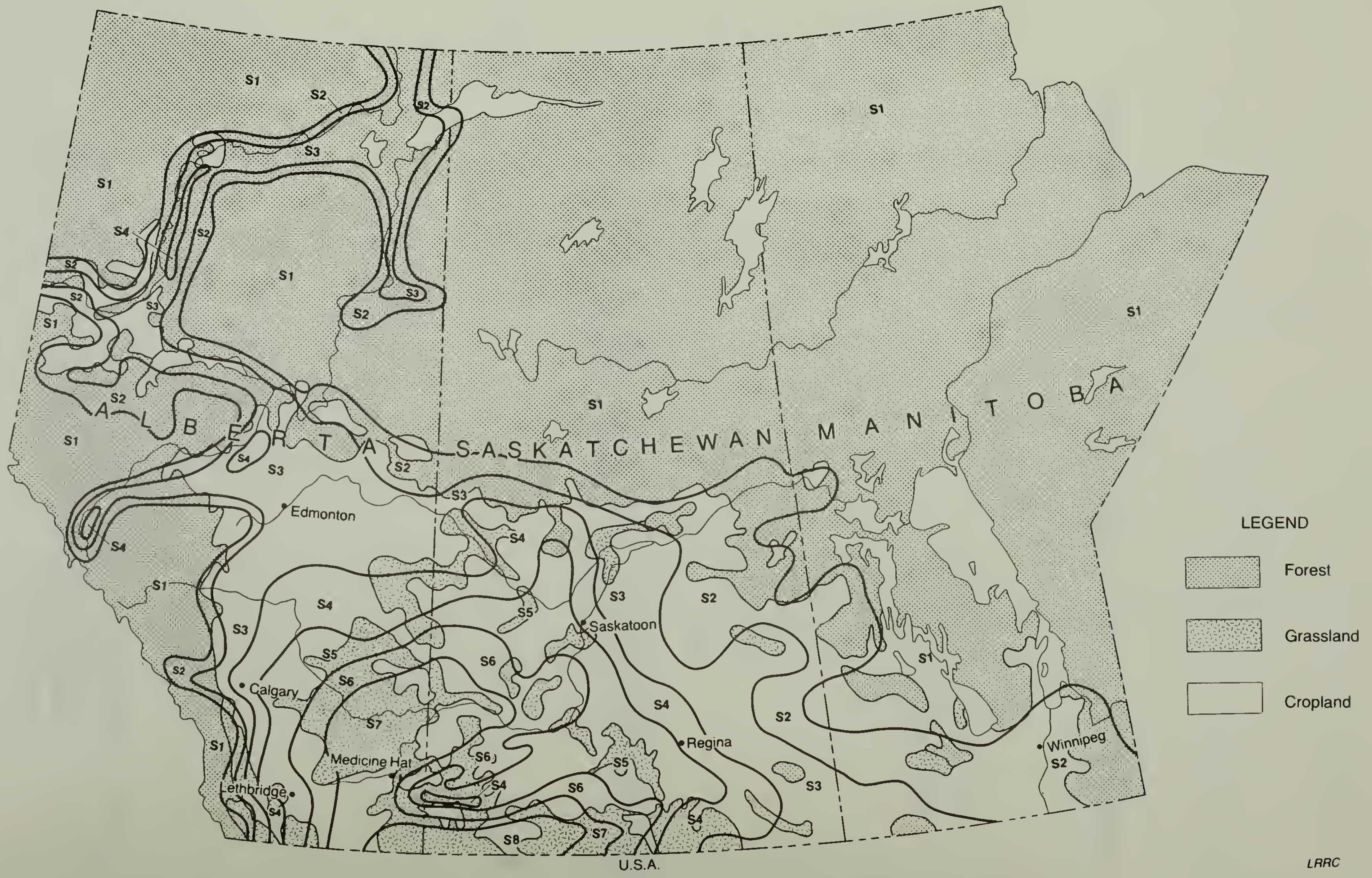


Fig. 3.7. Zones for soil moisture at seeding in relation to major land use categories (for legends see Tables 3.8 and 3.9).

Table 3.8. Range in soil water content at seeding for zones in Fig. 3.7, 150 mm AWC soil, 50% probability, for wheat-fallow and continuous wheat rotations and for the fallow year.

Zone	Range in soil moisture at seeding (mm)		
	wheat-fallow	continuous wheat	fallow year
S1	>140	>134	>136
S2	140-125	134-104	136-106
S3	125-110	104-74	106-75
S4	110-95	74-64	75-66
S5	95-80	64-55	66-57
S6	80-65	55-46	57-48
S7	65-50	46-36	48-38
S8	<50	<36	<38

water supply. This does not consider differences in yield that result from variations in growing season precipitation between zones.

The ranges in soil water contents at seeding in each zone in Fig. 3.7 for continuous wheat and for the fallow year in wheat-fallow rotation are presented in Table 3.8 for the 150 mm AWC, 50% probability level. These water contents were estimated from smooth curves drawn from plots of these variables against the "standard" variable (soil water content at seeding for wheat-fallow rotation, 150 mm AWC, 50% probability) for the 27 stations in this study. The results show that water contents at seeding for continuous wheat are very similar to those in the fallow year of a wheat-fallow rotation. Evidently the influence of summerfallowing on soil water does not carry over beyond one crop year. The values in Table 3.8 indicate that average amounts of water conserved by summerfallowing on soils with 150 mm AWC increased in a linear fashion from about 14 mm in the driest zone (S8) to 30-36 mm in zone S4. Conserved water decreased rapidly from 36 mm in zone S4 to only 6 mm in zone S1, the zone with highest moisture reserves in spring. Consequently, summerfallowing appears to be most effective in conserving moisture in zones S3 to S6 and least effective in the driest and wettest zones in the region. Assuming a constant WUE of 80 kg grain/ha/cm, as before, increases in yields due solely to extra moisture conserved by summerfallowing can be expected to average from 112-288 kg/ha in areas where moisture is limiting. In the wettest zones e.g. S1 and S2, additional soil water reserves in spring are not likely to influence yields significantly and may in fact depress yields due to excess moisture.

Soil water contents at seeding for all four AWC's and five probability levels used in this study are shown in Table 3.9 for each of the zone boundaries in Fig. 3.7. For each crop rotation, the water content for 150 mm AWC, 50% probability was used as a "standard" variable from which values for all other soils and probabilities were estimated. The mathematical expressions relating these variables are given in Appendix 3.2a, 3.2b and 3.2c. These were computed by applying stepwise linear regression procedures to the results of the analyses of the 27 climate stations used in this study.

Table 3.9. Estimated soil water content at seeding for zone boundaries in Fig. 3.7 at four soil AWC's and five probability levels. A. Wheat year, wheat-fallow rotation. B. Continuous wheat. C. Fallow year, wheat-fallow rotation.

		Soil water content at seeding (mm) not exceeded at given probability														
	Soil	A					B					C				
Zone	AWC	Probability (%)					Probability (%)					Probability (%)				
boundary	(mm)	10	25	50	75	90	10	25	50	75	90	10	25	50	75	90
S1-S2	100	83*	85*	86	88*	93*	82*	86	84*	88	91*	83*	86	84*	88	91*
	150	130*	138*	140	140*	141*	91*	104	134*	135	140*	92*	107*	136*	136	140*
	200	180*	182*	185	186*	190*	126*	150*	182*	191	186	128*	155*	183	189	191*
	250	230*	235*	238*	240*	242*	147	181	210*	228	242	160*	180*	212	235	243
S2-S3	100	69	77	82	86	91	45	67	81	84	90	48	67	81	84	90
	150	87	109	125	131	137	49	72	104*	125	136	55	76	106*	126	136
	200	133	158	174	181	186	72	95	132	163	180	90	111	145	170	183
	250	149	179	210	225	232	80	101	138	182	211	104	128	166	198	222
S3-S4	100	52	70	79	84	89	29	48	71	82	88	29	47	70	82	88
	150	54	77	110	127	134	31	48	74*	106	129	32	52	75*	107	130
	200	95	120	155	176	182	50	69	96	130	162	62	79	106	141	168
	250	99	127	166	206	225	54	72	100	137	173	69	89	118	152	187
S4-S5	100	42	62	76	84	89	26	41	64	81	87	25	41	64	81	87
	150	40	61	95	127	134	28	41	64*	98	124	27	45	66*	99	125
	200	77	100	136	176	182	45	63	86	117	152	53	70	94	130	159
	250	79	103	138	206	225	49	66	91	121	158	59	78	104	138	173
S5-S6	100	37	53	73	83	88	23	36	57	78	85	21	36	57	78	85
	150	36	53	80	115	131	24	36	55*	89	116	23	38	57*	90	117
	200	69	88	117	156	178	41	56	77	105	140	45	61	82	117	147
	250	73	93	120	162	198	43	60	82	108	143	49	67	91	122	157
S6-S7	100	31	43	67	81	88	19	30	48	73	82	18	30	49	73	83
	150	33	46	65	102	124	20	30	46*	78	106	19	31	48*	79	107
	200	60	76	98	136	167	35	48	66	92	125	37	52	72	102	132
	250	66	82	103	137	174	37	51	71	94	127	39	55	77	105	138
S7-S8	100	20	32	51	71	84	13	23	38	62	78	15	24	39	64	79
	150	22	30	50	76	102	14	25	36*	63	88	16	23	38*	64	90
	200	42	55	79	107	136	26	35	53	76	104	28	41	59	82	109
	250	42	57	79	110	141	27	37	54	79	106	28	43	62	84	113

* values determined manually from graphs

It should be noted that water contents for the zone boundary S1-S2 were estimated by visual inspection of plotted data since these points were outside the range of data from the 27 stations used in the regressions. Extrapolation beyond the range of the data can produce unreliable results, particularly when the regression is non-linear.

An example will help to illustrate the proper interpretation of Table 3.9. The data indicates that in 1 year in 10 (i.e. 10% probability value) the soil water content at seeding following the year of summer fallow will be less than 22 to 33 mm for soils with 150 mm AWC in zone S7. Equivalent values for continuous wheat are 14 to 20 mm. In zone S5, water content at seeding following summerfallow will exceed 131 to 134 mm in 1 year in 10 (i.e. 90% probability value) for soils with 150 mm AWC. Equivalent water contents for continuous wheat are 116 to 124 mm.

The results indicate that summerfallowing is more effective in conserving water in soils with high AWC. In zones S1 to S4, an average of 22 to 51 mm of additional water is conserved under summerfallow in soils with 250 mm AWC compared to soils with 150 mm AWC. In the drier zones (S5 to S8) only about 13 mm of additional water is conserved (at 50% probability) in the 250 mm AWC soil. In years with abnormally dry spring moisture conditions (e.g. 10% probability level), summerfallowing contributed significant amounts of soil water in the moister zones (45 to 83 mm in zones S1 to S3 for soils with 200 and 250 mm AWC), but, in the driest zones (S6 to S8), summerfallowing contributed less than 30 mm of water in these years. Conversely, in years with abnormally high soil water content in spring (e.g. 90% probability level), summerfallowing contributed insignificant amounts of soil water in the moist zones (eg. S1 and S2) but added substantial amounts (30 to 67 mm) in the drier zones (S5 to S8) for soils with 200 and 250 mm AWC.

In dry years (i.e. 10% probability), increase in water conserved by summerfallowing on higher AWC soils is greater in the wetter zones than in the drier regions. For example, in zones S1 and S2, soils with 250 mm AWC conserve 31 to 44 mm of water more than 150 mm AWC soils. Equivalent amounts for zones S7 and S8 are 7 to 16 mm. In the abnormally wet years (i.e. 90% probability), the difference is greatest in the mid-zones. In zones S4 and S5 the 250 mm AWC soils conserve 40 to 57 mm more water than 150 mm AWC soils, while for zones S1, S2, S7 and S8 the equivalent amounts are all under 30 mm.

Probabilities of threshold soil water contents shown in Table 3.7 (i.e. 10, 25, 50, 75 and 90% of AWC) either not exceeded or exceeded at seeding are presented in Fig. 3.8 for wheat-fallow rotation and in Fig. 3.9 for in the fallow year. Fig. 3.9 also applies reasonably well to continuous wheat (stubble seeding). These figures were prepared by plotting the appropriate probabilities against the "standard" variable used to construct the zones in Fig. 3.7 (water content at seeding, 150 mm AWC, 50% probability). Smooth lines were hand drawn through the points, thus allowing probabilities of threshold values to be estimated for each zone from the graphs. Fig. 3.8 indicates, for example, that for soil with 150 mm AWC, the probability of a soil water content of less than 25% of AWC at seeding is about 20% in zone S6 for wheat-fallow rotation. Conversely, the probability that this level of soil water is exceeded is about 80% (8 years out of 10).

Although smooth curves could be drawn readily through probability values plotted on graphs, relatively large variations in probabilities were common

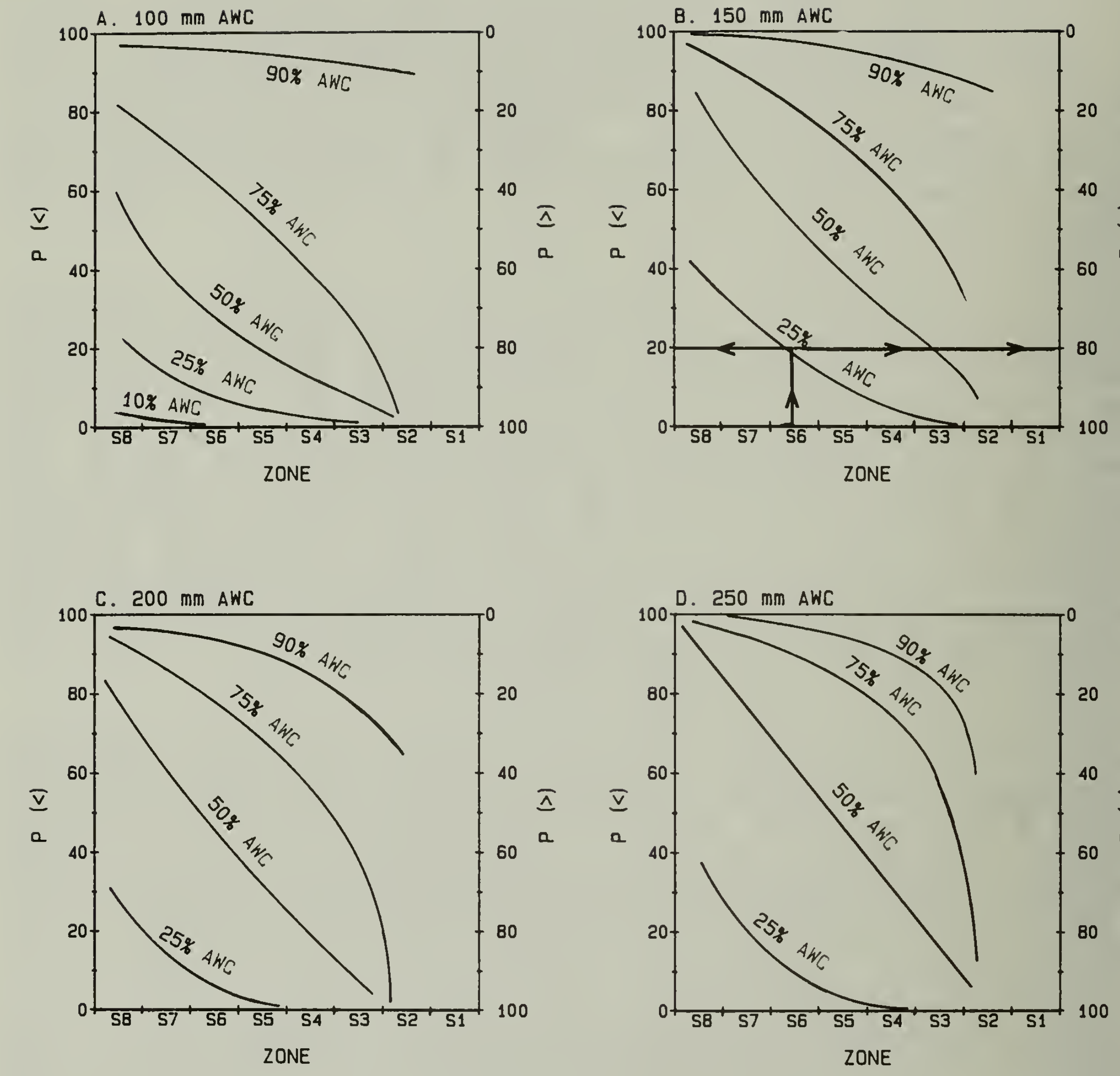


Fig. 3.8. Probability (P) that soil water content at seeding is less than (<) or greater than (>) selected thresholds (% of AWC) for four soil AWC's (100, 150, 200 and 250 mm) in relation to zones in Fig. 3.7, wheat-fallow rotation.

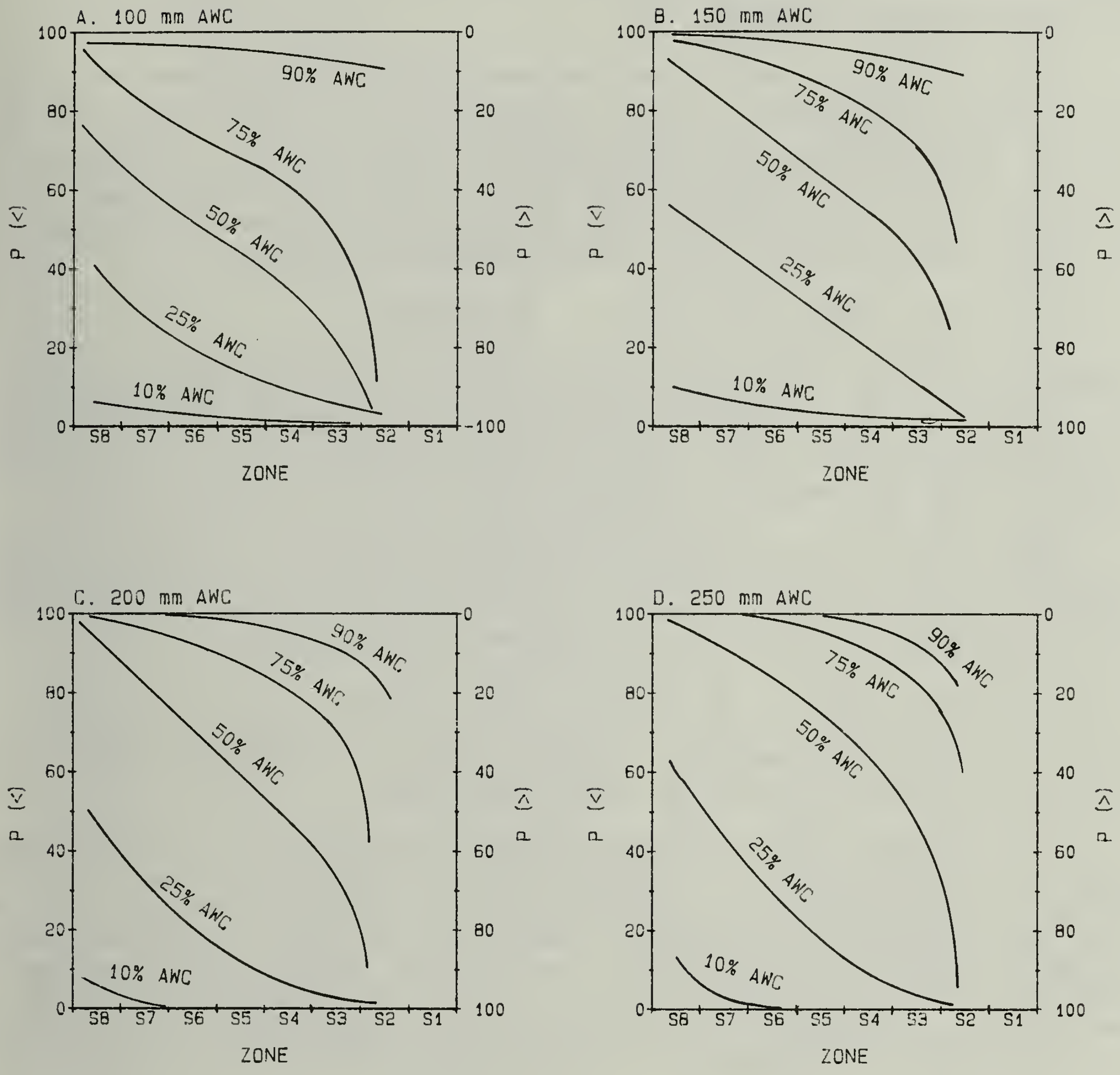


Fig. 3.9. Probability (P) that soil water content in the fallow year at seeding is less than (<) or greater than (>) selected thresholds (% of AWC) for four soil AWC's (100, 150, 200 and 250 mm) in relation to zones in Fig. 3.7, wheat-fallow rotation.

for climate stations in zones S2 and S3, particularly for the 75% AWC threshold. This was a result of stations having very similar median values (i.e. 50% probability) but different frequency distributions. Consequently the mean and median soil water content at seeding could differ by up to 15 mm at some locations for soils with 150 and 200 mm AWC.

Soil Water Content at Heading

Water content at heading was analyzed using similar procedures as for water content at seeding. The water content for 150 mm AWC, 50% probability for the wheat-fallow rotation was used as the "standard" variable for mapping. Station density was again increased by making use of data previously computed by Sly (unpublished data) for the 1941-70 and 1950-79 periods. Sly's data were highly correlated with the water contents at heading computed in this study, as expressed by the following regression equation:

$$Y = -0.72 + 1.039X \qquad R^2 = 0.83 \qquad SE = 6.9 \text{ mm}$$

where Y is the soil water content at heading for the 1925-84 period, and X is Sly's value for May 20 seeding (both are for 150 mm AWC, 50% probability, wheat fallow rotation). This equation indicated no significant bias from the 1:1 relationship and therefore only minor adjustments to Sly's data were necessary based on geographic patterns of residuals from this regression.

Zones for soil water content at heading were mapped on the basis of class intervals of 10 mm for 150 mm AWC, 50% probability, wheat-fallow rotation (Fig. 3.10, Table 3.10). Water contents for continuous wheat (Table 3.10) were estimated using the following linear regression equation:

$$Y = -5.53 + 0.913X \qquad R^2 = 0.92 \qquad SE = 4.5 \text{ mm}$$

where Y is water content for continuous wheat, X is water content for wheat-fallow rotation (150 mm AWC, 50% probability).

For the wheat-fallow rotation, average water contents at heading range from over 65 mm in zone H1 to less than 15 mm in zone H7 for the 150 mm AWC soils. Water contents for continuous wheat are on average about 7 to 10 mm lower than wheat-fallow. These differences are less than at seeding, except for the wettest zones, and reflect the increased water use from seeding to heading by fallow seeded crops of about 7 mm in the driest zone to 25 mm in the intermediate zones. In the wettest regions water use by fallow seeded crops during this growth period is no greater than for continuous wheat.

Estimates of soil water contents at heading are given for four soil AWC's and five probability levels in Table 3.11, based on regression equations in Appendix 3.3a and 3.3b. Increases in soil water contents under summerfallow rotation are greater for soils with high AWC's, reaching a maximum of 37 mm for the 250 mm AWC soil in zone H1 at the 50% probability level. In abnormally dry years (e.g. 10% probability) increases in water content at heading due to summerfallowing are relatively small (<10 mm) in the driest zones (e.g. H6 and H7), even for soils with high AWC. Soil texture (AWC) has a greater influence on actual water content at heading in wetter zones than in drier regions.

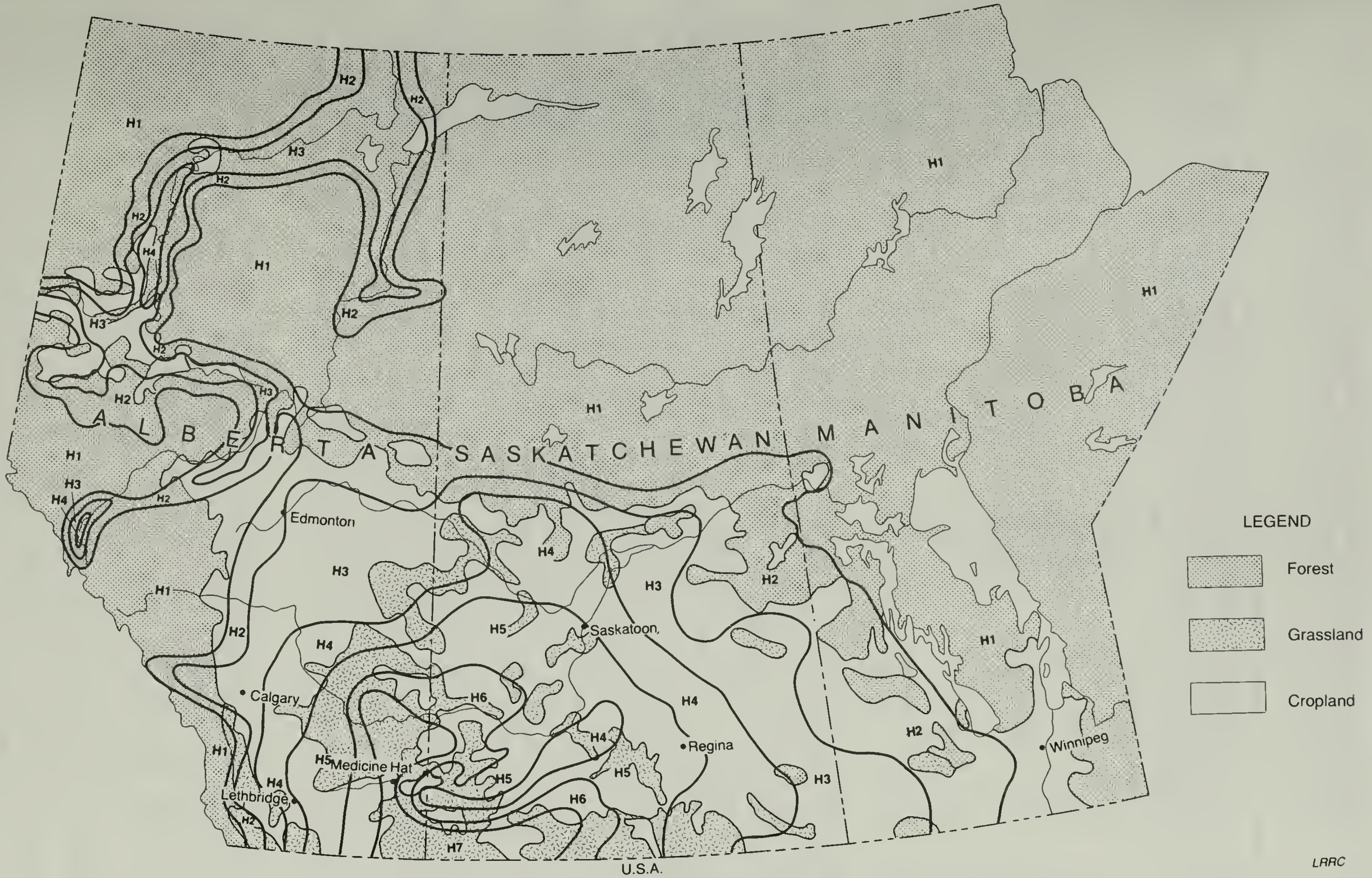


Fig. 3.10. Zones for soil moisture at heading, stress indices and water deficits for spring wheat in relation to major land use categories (for legends see Tables 3.10, 3.11, 3.12, 3.13 and 3.14).

Table 3.10. Range in soil water contents at heading for zones in Fig. 3.10 for wheat-fallow and continuous wheat rotations, 150 mm soil AWC, 50% probability.

Zone	Range in soil water content at heading (mm)	
	wheat-fallow	continuous wheat
H1	>65	>54
H2	65-55	54-45
H3	55-45	45-36
H4	45-35	36-26
H5	35-25	26-17
H6	25-15	17-8
H7	<15	<8

Probabilities that threshold soil water contents at heading are exceeded or not exceeded are presented in Fig. 3.11 for wheat-fallow rotation and Fig. 3.12 for continuous wheat. These figures were prepared in a similar manner as for water content at seeding by plotting the probabilities against the "standard" variable (water content at heading for 150 mm AWC, 50% probability). Wheat is known to be most sensitive to moisture stress around the heading stage. The soil moisture content at which actual evapotranspiration (AET) is reduced and yields are affected depends on a number of factors including soil physical characteristics, plant physiological factors and atmospheric demand. Although the precise influence of these factors is not fully understood, it is common to assume that soil water in excess of 50% of AWC is readily available (Baier, 1967; Shields and Sly, 1984). A recent study in the U.S.A. seems to confirm that AET begins to decrease when soil water drops below 50% available water (Brun et al. 1985). Comparison of Figs. 3.11 and 3.12 indicates that summerfallowing has a relatively small effect on the probability of water contents less than 50% AWC for soils with 100 and 150 mm AWC. The probability of reaching this water content is generally more than 80%, except in zones H1 and H2, indicating that some moisture stress is experienced in most years. The effect of summerfallowing is somewhat larger on soils with 200 and 250 mm AWC. Probabilities of water contents less than 50% AWC are reduced by about 10 to 20% by summerfallowing on these soils.

Soil texture (AWC) has a relatively small effect on the probabilities of most of the selected soil water content thresholds (expressed as a percentage of available water), except for the wetter zones. In zones H3 to H1, soils with high AWC's have significantly lower probabilities of reaching water contents of 50% of AWC or less. The influence of AWC is greater for wheat-fallow rotations than for continuous wheat.

Stress Indices and Water Deficits for Wheat

The ratio of actual to potential evapotranspiration (AET/PET) has been used in crop growth models to relate relative yield decreases due to moisture

Table 3.11. Estimated soil water content at heading for zone boundaries in Fig 3.10 for four soil AWC's and five probability levels. A. Wheat-fallow rotation; B. Continuous wheat.

Zone Boundary	Soil AWC (mm)	Soil water content at heading (mm) not exceeded at given probability									
		A. Wheat-fallow					B. Continuous wheat				
		Probability (%)					Probability (%)				
		10	25	50	75	90	10	25	50	75	90
H1-H2	100	15	23	34	53	79	11	20	34	50	74
	150	35	49	65	89	119	17	32	54	78	108
	200	78	93	117	138	166	43	62	91	123	154
	250	108	125	150	179	206	53	74	113	149	181
H2-H3	100	12	18	30	49	72	9	16	29	47	70
	150	24	38	55	78	106	11	23	45	70	99
	200	60	78	101	127	155	32	48	76	113	142
	250	77	97	126	164	194	38	56	94	131	163
H3-H4	100	10	15	26	44	64	7	13	24	43	64
	150	15	27	45	67	93	7	16	36	61	89
	200	44	62	84	114	142	23	37	62	98	127
	250	52	72	103	141	174	26	42	75	110	143
H4-H5	100	7	12	22	39	56	4	9	19	38	57
	150	9	18	35	56	80	4	11	26	50	77
	200	30	45	68	99	127	15	26	47	78	110
	250	33	51	80	112	147	18	30	55	85	120
H5-H6	100	4	9	17	33	49	2	6	14	30	47
	150	4	11	25	45	67	3	7	17	38	61
	200	19	30	52	80	107	10	18	32	55	88
	250	20	34	56	80	115	12	21	36	58	92
H6-H7	100	2	5	13	25	41	0	3	7	17	31
	150	2	6	15	34	54	2	4	8	21	39
	200	11	18	32	56	86	5	10	18	36	56
	250	14	22	36	58	91	7	13	18	40	56

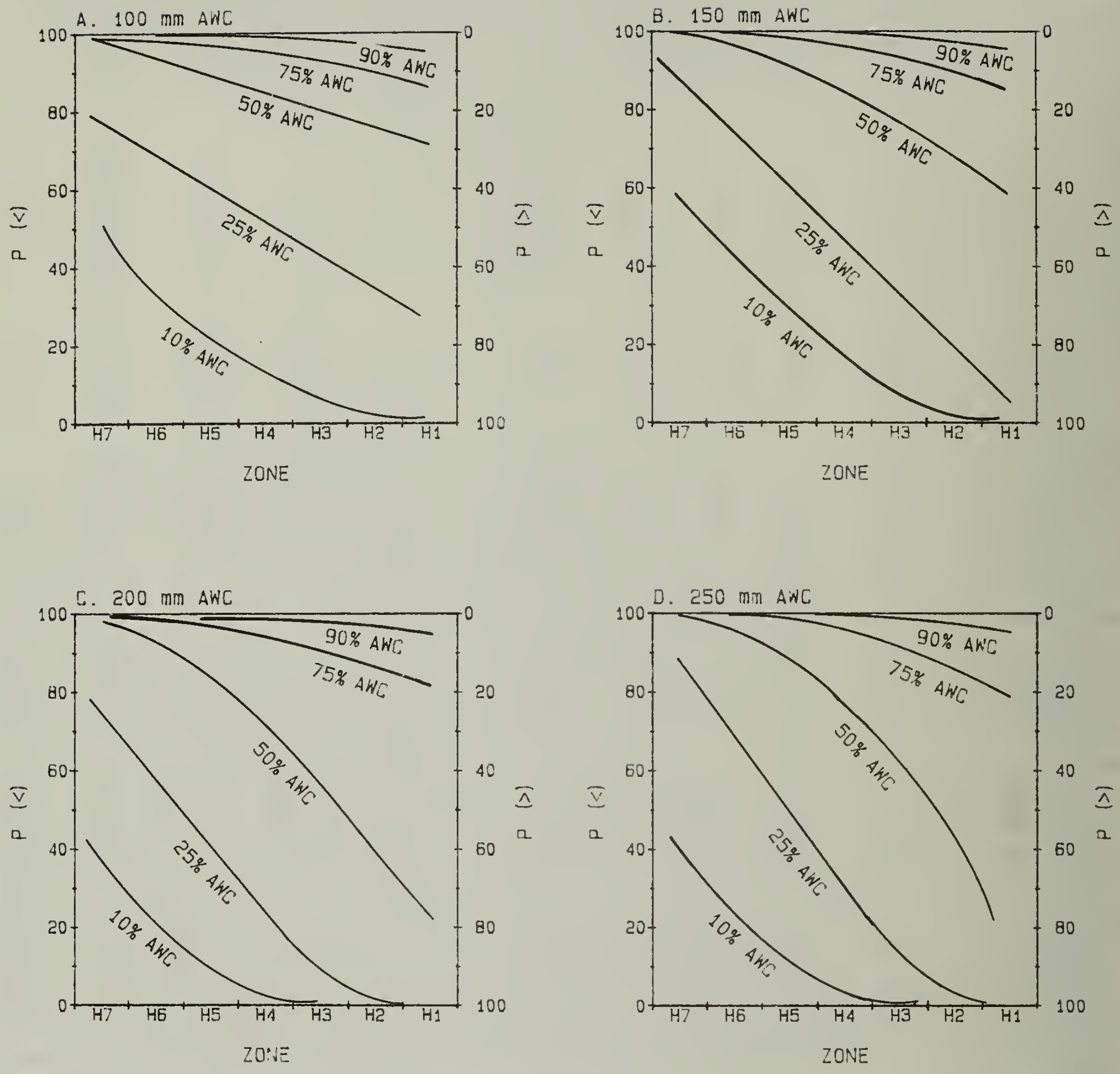


Fig. 3.11. Probability (P) that soil water content at heading is less than (<) or greater than (>) selected thresholds (% of AWC) for four soil AWC's (100, 150, 200 and 250 mm) in relation to zones in Fig. 3.10, wheat-fallow rotation.

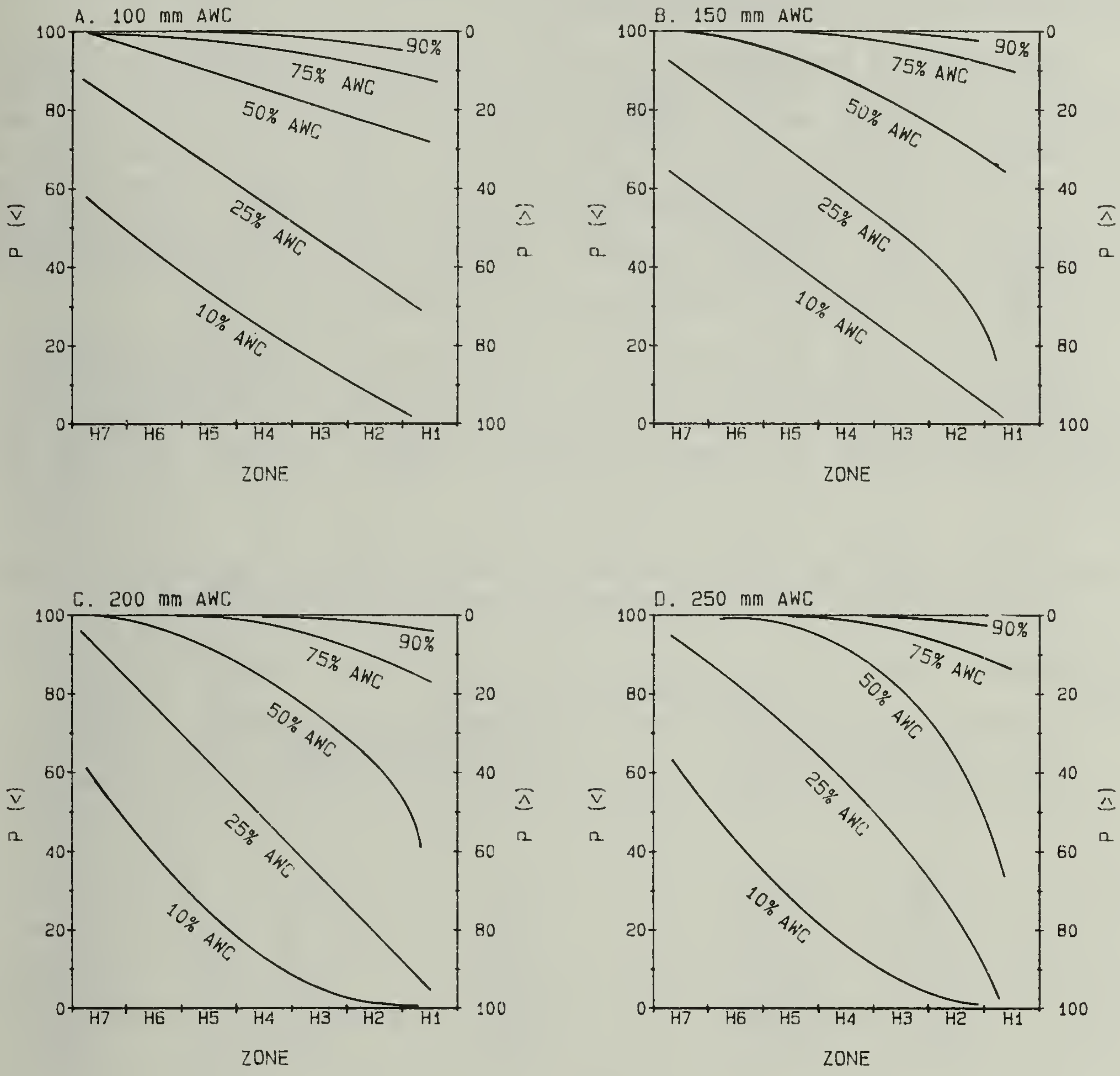


Fig. 3.12. Probability (P) that soil water content at heading is less than (<) or greater than (>) selected thresholds (% of AWC) for four soil AWC's (100, 150, 200 and 250 mm) in relation to zones in Fig. 3.10, continuous wheat.

stress to the relative evapotranspiration deficit (Doorenbos and Kassam 1979; Stewart 1983). In this study, daily water stress indices defined as (1-AET/PET), were accumulated from seeding till harvest and from jointing till soft dough using the results from the modified VSMB described earlier. The latter period is the most critical with regard to yield reductions in that the crop is most sensitive to water stress at that time (Robins and Domingo 1962; Bauer 1972; Desjardins and Ouellet 1980).

Water deficits (also known as aridity indices or irrigation requirements) were also determined in this study based on methodologies described by Sly (1982) and by Shields and Sly (1984). The only adaptation in this study was that seeding, emergence and soft dough dates of wheat varied from year to year, according to the estimates by the VSMB and the biometeorological time scale. In this study, water deficits were calculated only for the wheat-fallow crop rotation. Water deficits essentially represent the deficiency of natural precipitation in maintaining soil moisture levels above 50% of AWC and maintaining crop transpiration at potential.

Stress indices and water deficits for wheat (150 mm AWC, 50% probability) were highly correlated with soil moisture at heading ($-0.95 \leq r \geq +0.95$), and consequently the zonation map in Fig. 3.10 could be used to describe the spatial distribution of these variables. Ranges for each variable are presented in Table 3.12 and were estimated using the regression equations reported in Appendix 3.4a. The effect of summerfallowing on the average stress index is not large but fairly consistent over all zones with an average decrease of about 3 to 4 units. Average water deficits range from less than 117 mm in zone H1 to over 280 mm in zone H7.

Table 3.12. Range in stress indices and water deficits for wheat for each zone in Fig. 3.10, 150 mm soil AWC, 50% probability.

Zone	Accumulated stress index				Wheat water deficit (mm)
	seeding-harvest		jointing-soft dough		
	w/f*	cw*	w/f	cw	
H1	<23	<27	<4	<7	<117
H2	23-30	27-33	4-8	7-11	117-150
H3	23-36	33-39	8-12	11-15	150-182
H4	36-42	39-45	12-16	15-19	182-215
H5	42-48	45-52	16-20	19-23	215-248
H6	48-55	52-58	20-24	23-26	248-280
H7	>55	>58	>24	>26	>280

* w/f = wheat fallow rotation; cw = continuous wheat

Stress indices and water deficits for various soil textures (AWC's) and probability levels are presented in Tables 3.13 and 3.14. These estimates

Table 3.13. Estimated accumulated stress indices for wheat for zone boundaries in Fig. 3.10 for four soil AWC's and five probability levels, seeding to harvest and jointing to soft dough, wheat-fallow rotation and continuous wheat.

		Accumulated stress index not exceeded at given probability level																			
		Seeding to harvest										Jointing to soft dough									
	Soil	wheat-fallow					continuous wheat					wheat-fallow					continuous wheat				
Zone	AWC	Probability (%)					Probability (%)					Probability (%)					Probability (%)				
Boundary	(mm)	10	25	50	75	90	10	25	50	75	90	10	25	50	75	90	10	25	50	75	90
H1-H2	100	15	23	32	40	50	17	25	33	43	52	-1	4	10	16	22	-1	5	11	17	24
	150	7	15	23	32	41	10	18	27	38	48	-6	0	4	10	16	-4	1	7	15	22
	200	8	13	19	28	37	9	16	24	35	45	-5	-1	3	8	13	-4	1	6	13	19
	250	4	9	16	24	32	7	13	23	33	43	-6	-2	0	6	11	-5	0	6	12	19
H2-H3	100	20	28	37	46	54	20	28	38	48	56	0	6	13	19	24	0	7	14	20	26
	150	12	20	30	40	49	14	23	33	44	53	-4	1	8	15	21	-2	3	11	19	26
	200	10	17	26	35	43	13	20	31	41	51	-4	0	6	12	17	-2	3	10	18	23
	250	7	14	23	33	41	11	19	30	40	49	-5	-1	5	11	16	-2	3	10	17	24
H3-H4	100	24	32	42	51	58	24	33	42	52	60	2	8	15	22	27	3	9	17	23	29
	150	18	26	36	47	55	19	28	39	50	58	-2	4	12	19	25	1	7	15	23	29
	200	15	22	32	41	49	18	26	37	48	56	-2	3	10	16	21	1	6	14	22	27
	250	12	20	30	40	48	16	25	36	47	54	-2	2	9	15	20	2	7	14	21	27
H4-H5	100	29	37	46	55	62	29	37	47	56	63	5	11	18	24	29	7	12	20	26	31
	150	23	32	42	53	61	24	34	45	56	63	1	7	16	23	28	4	11	19	27	32
	200	20	28	38	47	55	23	32	43	53	61	1	6	14	20	25	5	10	18	25	30
	250	19	27	37	47	54	22	32	43	53	60	1	6	13	19	24	6	11	18	25	30
H5-H6	100	33	41	50	59	66	35	43	53	62	68	8	14	21	27	32	11	16	23	29	34
	150	29	38	48	58	66	32	41	52	62	68	6	12	20	27	32	8	16	23	30	34
	200	26	34	44	53	60	30	39	50	60	66	5	10	17	24	29	9	15	22	28	33
	250	25	34	43	53	60	30	39	50	60	66	5	10	18	24	29	10	16	22	29	33
H6-H7	100	38	46	56	64	71	41	48	58	66	72	13	18	24	30	34	13	19	25	32	36
	150	35	44	55	64	72	39	47	58	66	72	11	18	24	30	34	12	20	26	32	36
	200	33	40	51	59	67	37	46	56	65	72	9	16	21	28	33	12	20	25	30	35
	250	32	40	51	59	67	38	46	56	65	72	9	16	22	28	33	13	20	25	31	35

Table 3.14. Estimated water deficits of wheat for zone boundaries in Fig. 3.10, at four soil AWC's and five probability levels.

Zone Boundary	Soil AWC (mm)	Wheat water deficit not exceeded (mm)					Zone Boundary	Soil AWC (mm)	Wheat water deficit not exceeded (mm)				
		Probability (%)							Probability (%)				
		10	25	50	75	90			10	25	50	75	90
H1-H2	100	70	103	144	185	232	H4-H5	100	123	166	215	260	292
	150	43	81	117	165	215		150	115	161	215	269	310
	200	20	56	90	144	186		200	92	142	200	253	297
	250	9	35	79	128	174		250	99	152	212	268	317
H2-H3	100	84	122	168	211	248	H5-H6	100	149	191	238	285	319
	150	56	99	150	200	247		150	150	198	248	304	342
	200	31	70	127	177	223		200	131	185	237	295	334
	250	22	62	124	175	227		250	146	203	257	315	357
H3-H4	100	102	143	191	235	268	H6-H7	100	177	216	261	310	347
	150	81	127	182	234	279		150	180	232	280	338	373
	200	56	101	163	213	259		200	164	224	273	336	370
	250	54	102	167	221	273		250	184	247	300	361	393

were determined using the regression equations in Appendix 3.4 (b, c, d, e and f). Negative values for the stress indices for jointing to soft dough at low probabilities in some wetter zones are due to the fact that AET is allowed to exceed PET in the VSMB under some conditions. Water deficits (Table 3.14) are occasionally higher for soils with greater AWC in the drier zones. This is because more water is needed to bring these soils up to field capacity in the spring.

Probabilities that threshold levels for stress indices from jointing to soft dough, and that wheat water deficits are either exceeded or not exceeded are presented in Fig. 3.13-3.15. The relative frequency of droughts can be readily assessed if a drought can be defined in terms of a critical threshold value of these indices. For example, Fig. 3.15 indicates that if water deficits of 350 mm or more constitute a serious drought for wheat for soils with 150 mm AWC, then this event occurs with a probability (P) of 20% or greater in zone H7, 20-10% in zone H6 and 10% or lower in zone H5. Return periods T (where T = 100/P) for this event are 5 years or less for zone H7, 5 to 10 years for zone H6 and 10 years or more for zone H5. Water deficits above 350 mm are very rare in zones H3 to H1. Soil texture has a relatively small effect on water deficit probabilities in comparison to geographic location.

Comparisons of Figs. 3.13 and 3.14 indicate that AWC has a greater influence on stress index probabilities for the wheat-fallow rotation than for continuous wheat, as was the case with soil water content at heading. However, similar to

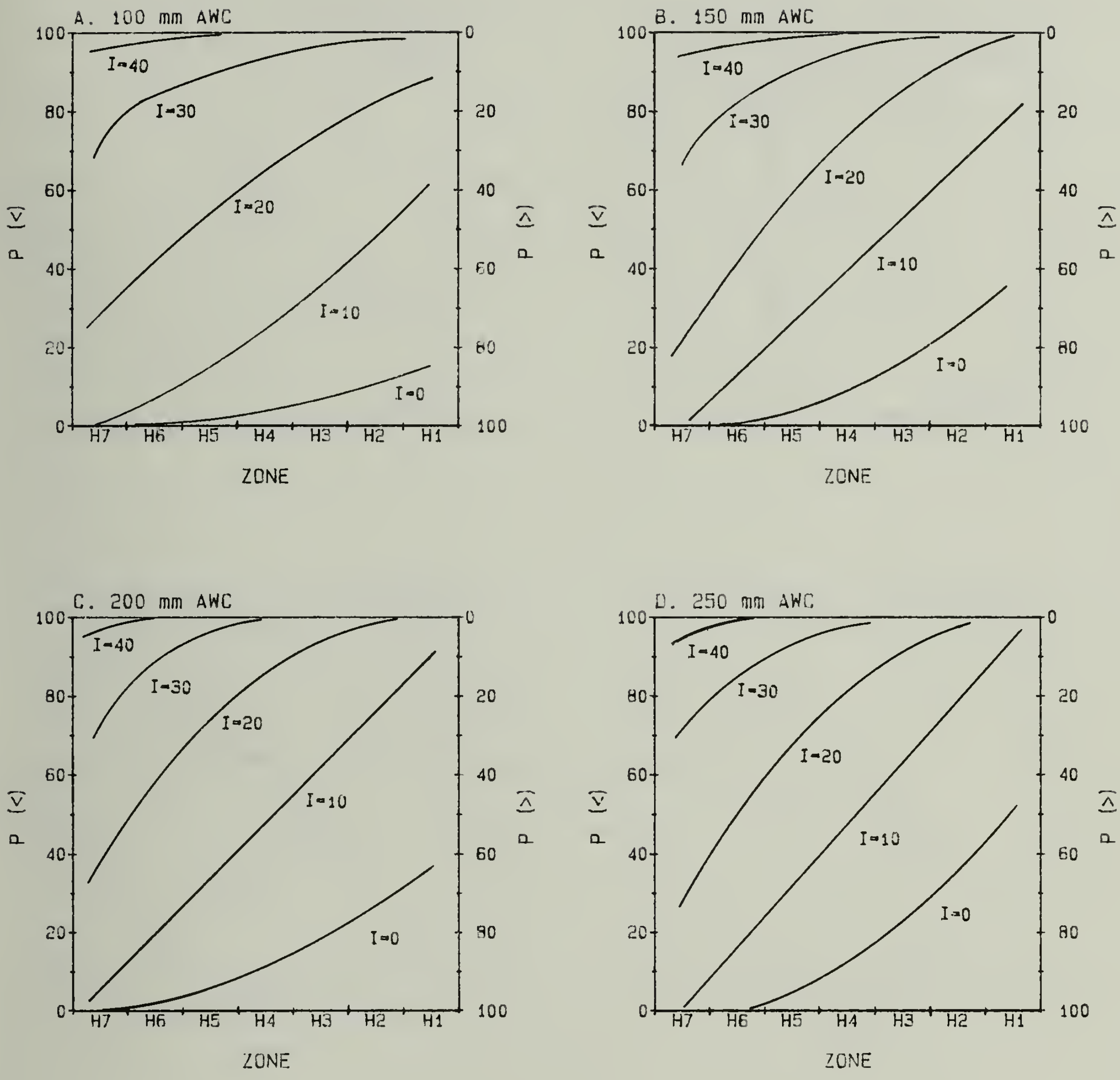


Fig. 3.13. Probability (P) that the stress index (I) from jointing to soft dough is less than (<) or greater than (>) selected thresholds for four soil AWC's (100, 150, 200 and 250 mm) in relation to zones in Fig. 3.10, wheat-fallow rotations.

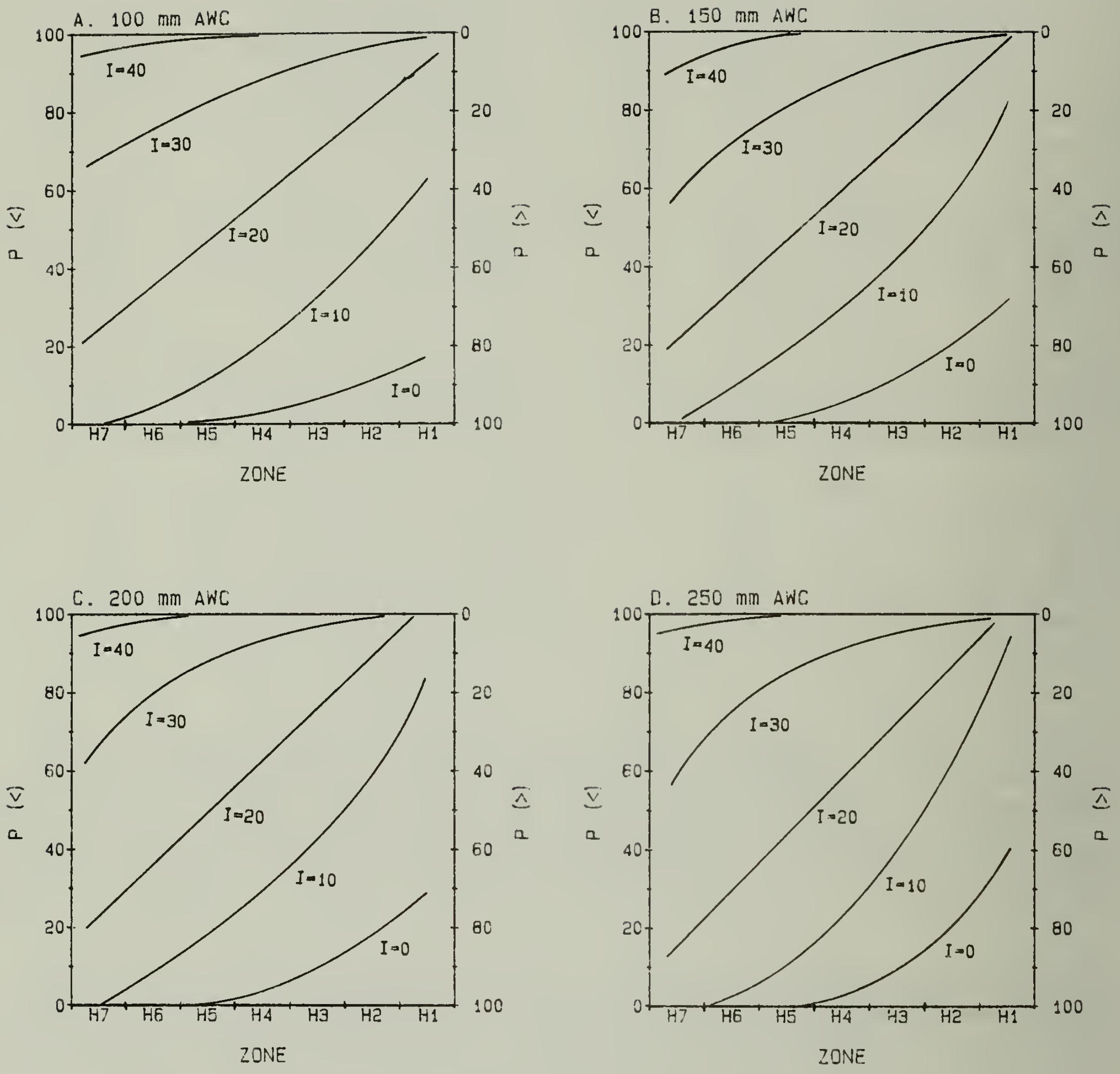


Fig. 3.14. Probability (P) that the stress index (I) from jointing to soft dough is less than (<) or greater than (>) selected thresholds for four soil AWC's (100, 150, 200 and 250 mm) in relation to zones in Fig. 3.10, continuous wheat.

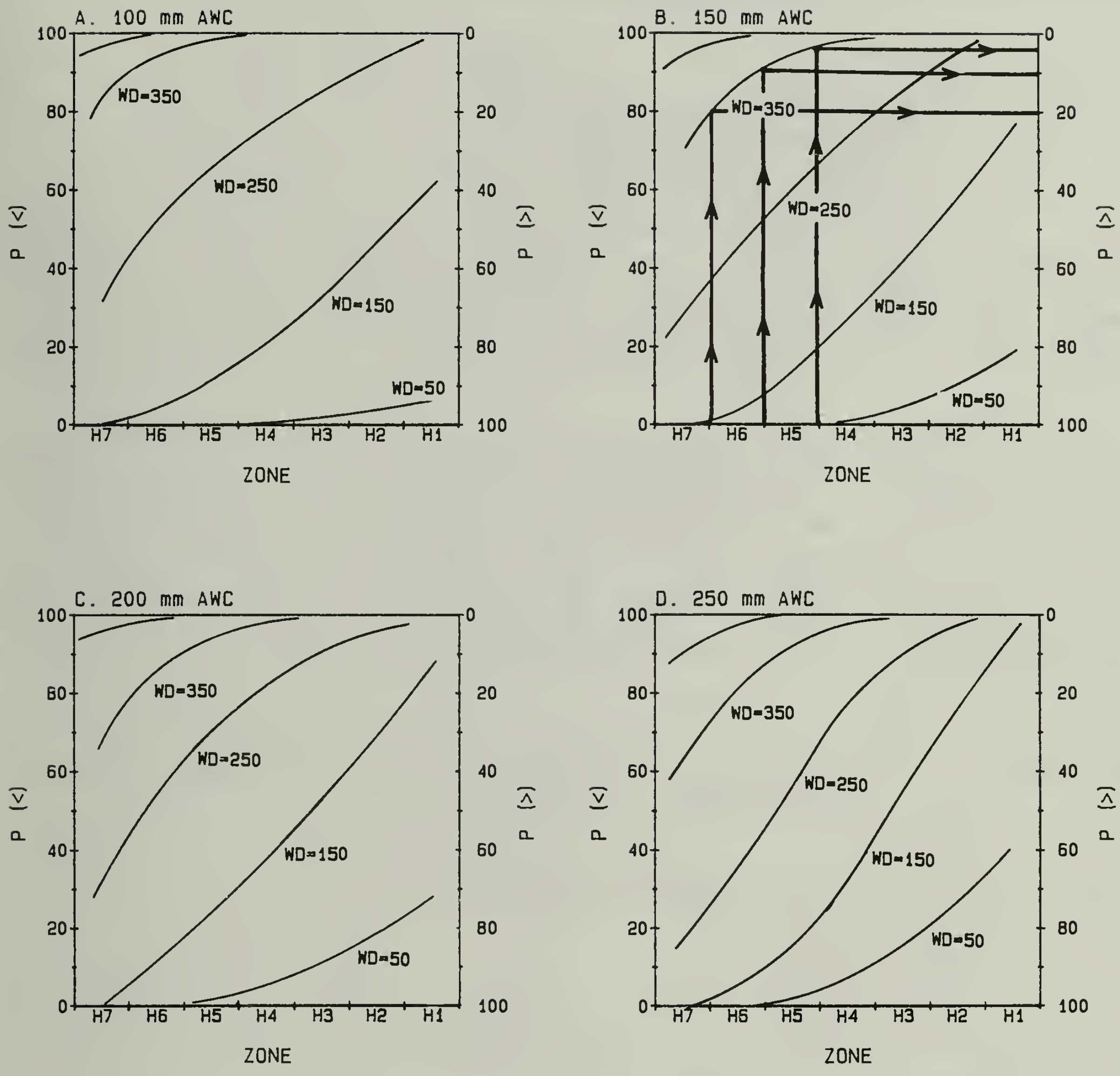


Fig. 3.15. Probability (P) that the wheat water deficit (WD) is less than (<) or greater than (>) selected thresholds for four soil AWC's (100, 150, 200 and 250 mm) in relation to zones in Fig. 3.10, wheat-fallow rotation.

water deficits, the influence of AWC is usually small in comparison to the location effects. Stress index probabilities are significantly higher for continuous wheat than for the wheat-fallow rotation and the effect of rotation is greater at high AWC's.

Thermal Resources for Maturing Wheat and Barley

Maturity dates for wheat and barley were determined using the biometeorological timescales of Robertson (1968) and Williams (1974), respectively. Both these timescales, which use air temperature and photo period data as input, were started on the seeding date as estimated by the VSMB. Thermal resources for each crop were defined as the number of days from maturity until the day when the minimum temperature dropped below 0°C and below -2°C. The latter criteria was chosen as it was felt to be important with regard to grain quality deterioration. Available thermal resources have been described previously by Williams and Oakes (1978) and Sly (1982), using climatic normal data and a derived 0°C frost date. The present study used observed frost dates and also described seasonal variability of the thermal resources.

Thermal resources for wheat and barley for both 0°C and -2°C were highly correlated ($r \geq 0.90$), and one zonation map (Fig. 3.16) adequately described these two parameters. Days between barley ripening and first frost (0°C), 50% probability, 150 mm AWC, was used as the standard for mapping, and the other parameters were estimated from it using regression equations (Appendix 3.5 (a)). The range for each parameter at the 50% probability level in relation to four map zones (T1-T4) is given in Table 3.15. Since differences between soils were small (1 to 2 days), the values apply equally well to all soil textures (AWC's).

Table 3.15. Thermal resources for maturing wheat and barley for zones in Fig. 3.16, 50% probability level.

Zone	Days between ripening and first frost			
	Barley		Wheat	
	0°C	-2°C	0°C	-2°C
T1	<25	<49	<16	<41
T2	25-40	49-55	16-32	41-47
T3	40-55	55-68	32-48	47-61
T4	>55	>68	>48	>61

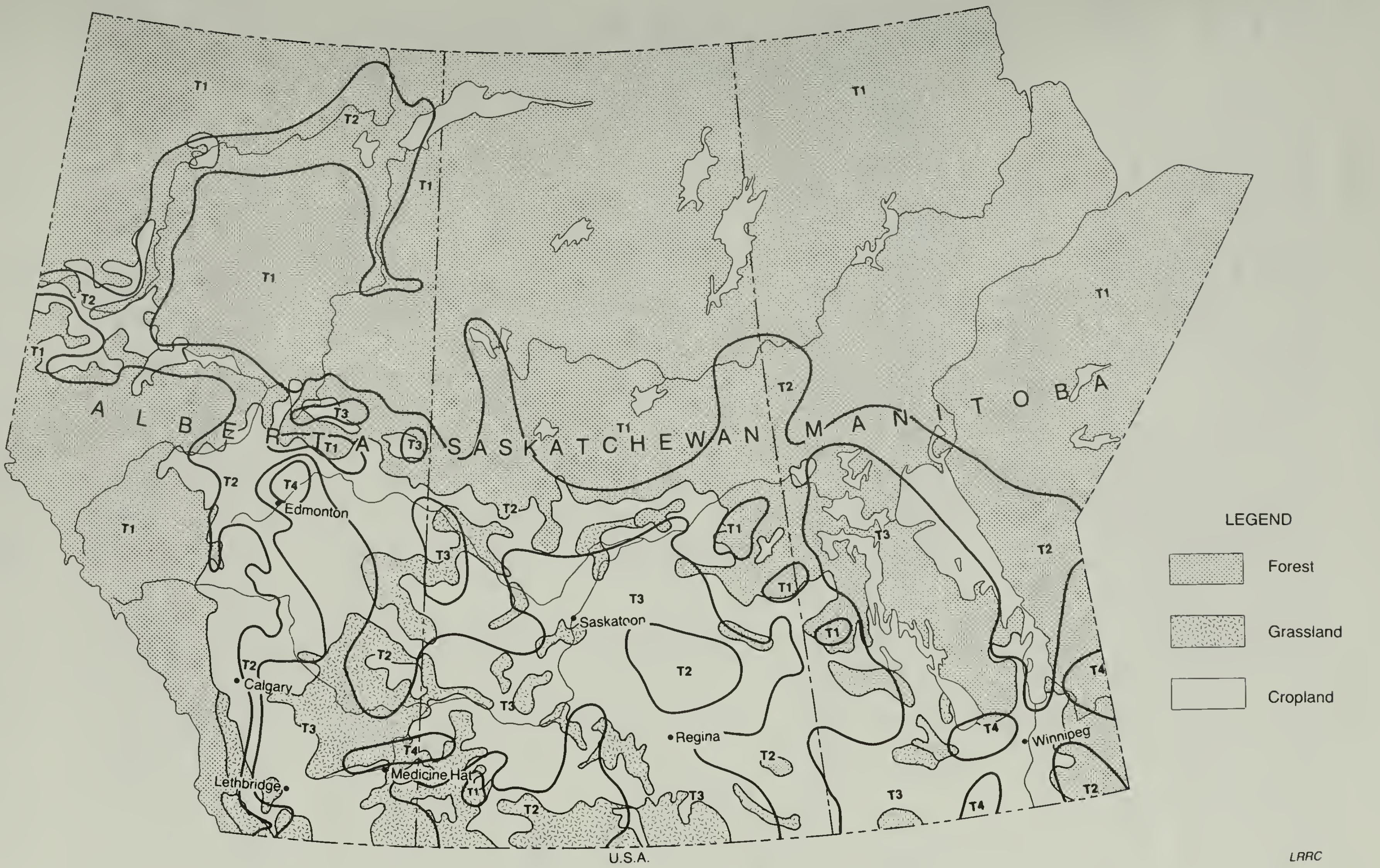


Fig. 3.16. Zones of thermal resources for maturing wheat and barley (for legends see Tables 3.15 and 3.16).

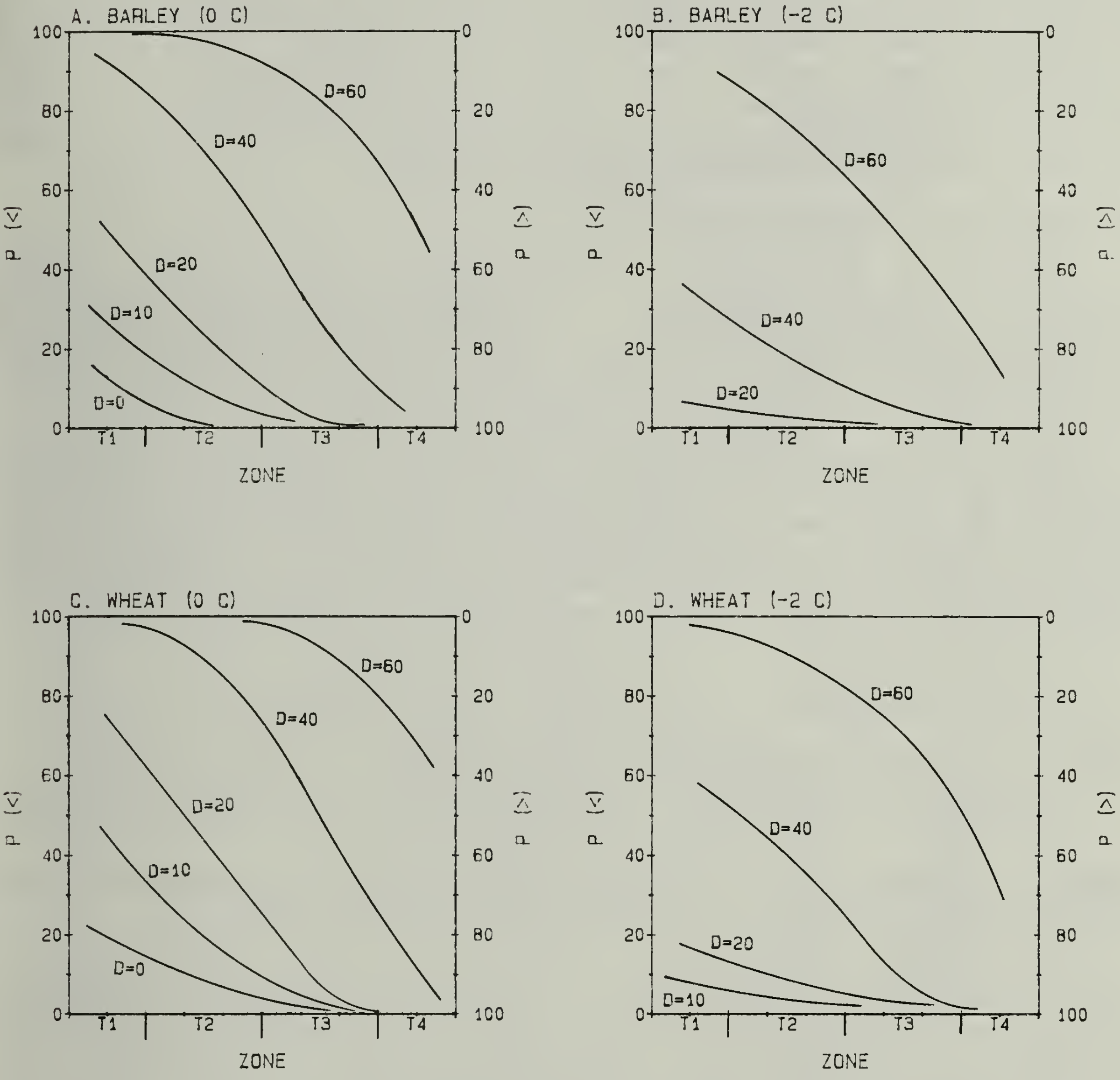
Zone boundaries in Fig. 3.16 were positioned with the help of previously mapped data for the 1941-70 period (Sly 1982). Estimates of this variable obtained from Sly's map were highly correlated ($r \geq 0.84$) with values computed in this study for the 27 stations (station data were not available for the 1941-70 period). However, Sly's values averaged about one week longer and this difference was taken into account in the mapping procedure.

Thermal resources at five probability levels for the zone boundaries are shown in Table 3.16. The 10, 25, 75 and 90% probabilities were estimated using regression equations (Appendix 3.5(b)). Results show that in most zones the thermal resources are not a major limiting factor under present climatic conditions. However, in zones T1 and part of T2, the first frost (0°C) occurs before the ripening date of wheat in extreme years (i.e. about 1 year in 10). In these years loss in yield and quality due to frost may be expected. This analysis has not considered time required for harvesting. In some years or regions, lack of sufficient time for harvesting due to weather may result in loss of yield or quality of grain even though it has ripened before the first frost.

Table 3.16. Thermal resources for maturing wheat and barley for zone boundaries in Fig. 3.16, five probability levels.

Zone Boundary	Days between ripening and first frost - not exceeded at given probability levels									
	0°C					-2°C				
	Probability (%)					Probability (%)				
	10	25	50	75	90	10	25	50	75	90
A. Barley										
T1 - T2	6	15	25	34	44	32	41	49	59	67
T2 - T3	23	31	40	49	58	39	47	55	65	73
T3 - T4	40	47	55	64	73	53	60	68	78	86
B. Wheat										
T1 - T2	-5	7	16	26	33	21	33	41	49	58
T2 - T3	14	24	32	41	49	29	39	47	55	63
T3 - T4	34	41	48	56	64	47	54	61	69	77

Probabilities for selected threshold levels for thermal resources are presented in Fig. 3.17. These graphs indicate that 0°C frosts can occur before both wheat and barley mature ($D<0$) in zones T1 and T2. The occurrence



A. BARLEY (0 C)

B. BARLEY (-2 C)

C. WHEAT (0 C)

D. WHEAT (-2 C)

Fig. 3.17. Probability (P) that days between ripening and first frost (D) is less than (<) or greater than (>) selected thresholds in relation to zones in Fig. 3.16. A. Barley, 0°C. B. Barley, -2°C. C. Wheat, 0°C. D. Wheat, -2°C.

of a -2°C frost before maturity is quite rare in these zones, but can also happen.

It must be emphasized that, although these data are quite representative of each zone, considerable variation within zones is possible due to the effects of local topography on frost. For example, low lying areas with poor cold air drainage can form frost pockets which may experience frost as much as two weeks or more earlier than surrounding regions. Such areas have significantly higher probabilities of experiencing frost before maturity than shown in tables and graphs in this report. In some instances a -2°C frost could occur 20 days or more before maturity of wheat. The scale of this study does not allow for evaluation of these local factors.

Water Deficits for Perennial Forages

Methodologies for calculating water deficits (also known as aridity indices or irrigation requirements) for forages have been described by Sly (1982) and by Shields and Sly (1984). Water deficits for forages represent the deficiency of precipitation in maintaining soil moisture levels above 50% of AWC and maintaining evapotranspiration at potential.

Water deficit zones for perennial forages were constructed on the basis of the 150 mm soil AWC, 50% probability value (Fig. 3.18). Values range from less than 200 mm in zone D1 to over 550 mm in zone D9 (Table 3.17). Water deficits computed by Sly from the 1941-70 and 1950-79 periods were also used to increase station density for mapping. These values were adjusted to the 1925-84 period using the following linear regression equations:

$$Y = 9.95 + 0.9939 X_1 \qquad R^2 = 0.95 \qquad SE = 18.2 \text{ mm}$$
$$Y = 41.1 + 0.9401 X_2 \qquad R^2 = 0.98 \qquad SE = 12.2 \text{ mm}$$

where Y is the water deficit for the 1925-84 period,
X_1 and X_2 are water deficits from the 1941-70 and 1950-79 periods, respectively (150 mm AWC, 50% probability).

Geographic patterns of residuals from these regressions were used to make additional minor adjustments to the shorter term (30 yr) data.

Water deficits for the range of soil textures (AWC's) and probability levels are presented in Table 3.18, for each zone boundary in Fig. 3.18. Regression equations used to estimate these values from the 150 mm soil AWC, 50% probability level are shown in Appendix 3.6. Deficits range from a low of 2 mm (zone boundary D1-D2, 250 mm soil AWC, 10% probability) to a high of 681 mm (zone boundary D8-D9, 100 mm soil, 90% probability).

Probabilities that selected threshold values of forage water deficits are either exceeded or not exceeded are presented in Fig. 3.19. These permit a quick assessment of the relative frequency of droughts in each zone, provided that droughts can be linked to threshold values of the deficits. For example, if it can be assumed that a water deficit in excess of 450 mm results in a serious drought for forages, then Fig. 3.19 indicates that the probability (P) of this event is 10% or lower in zone D3, 20-30% in zone D5 and 50-65% in zone D7 for soils with 150 mm AWC. The return period T (where T = 100/P) for this

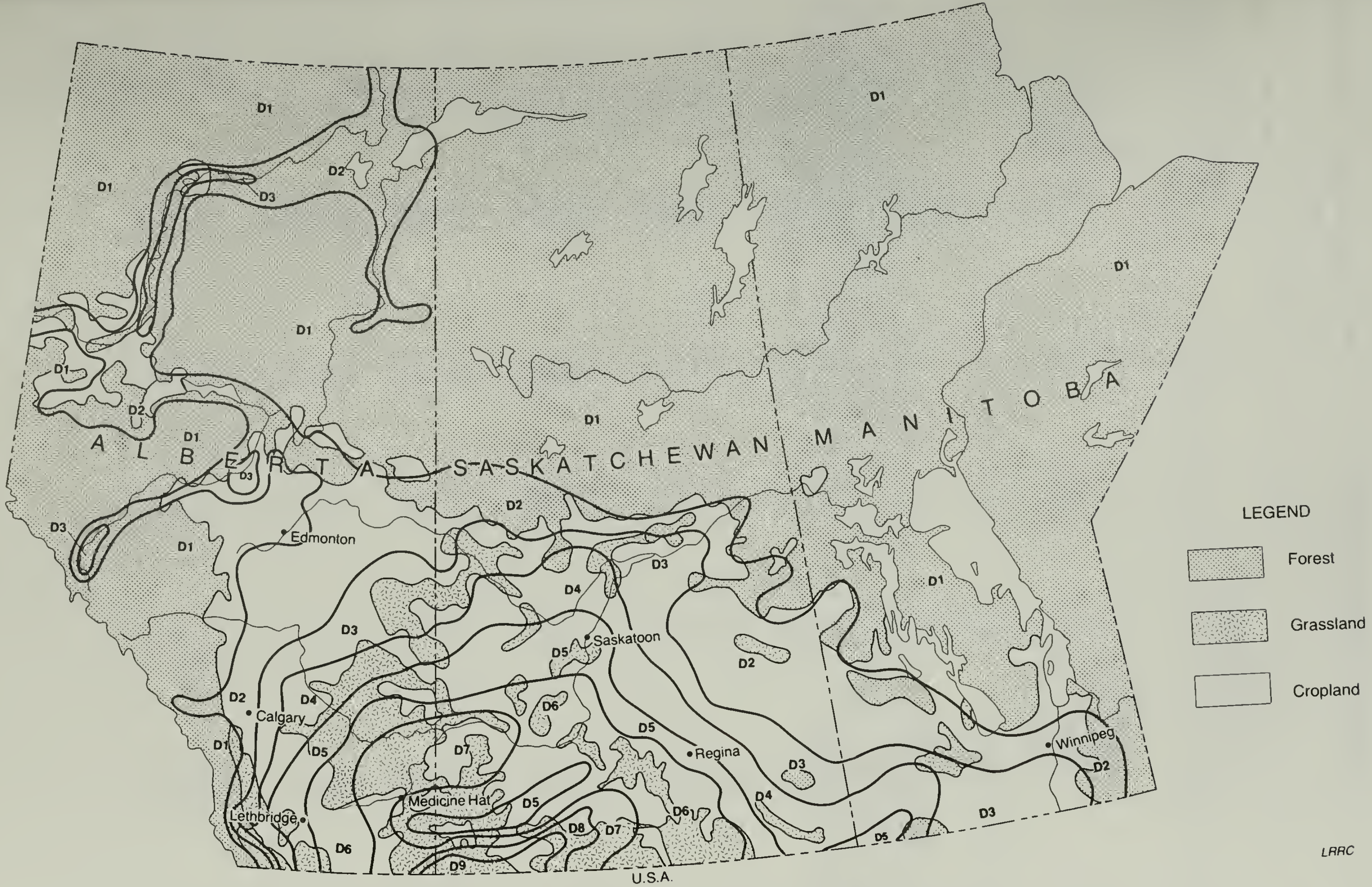


Fig. 3.18. Water deficit zones for perennial forages (for legends see Tables 3.17 and 3.18).

Table 3.17. Range in forage water deficits for each zone in Fig. 3.18, 150 mm soil AWC, 50% probability.

Zone	Forage water deficit (mm)	Zone	Forage water deficit (mm)
D1	<200	D6	400-450
D2	200-250	D7	450-500
D3	250-300	D8	500-550
D4	300-350	D9	>550
D5	350-400		

event is approximately 10 years or more in zone D3, 4 to 5 years in zone D5, and 1.5 to 2 years in zone D7. Soils with higher AWC have consistently lower probabilities (or longer return periods) for selected deficit values being exceeded. For example, the return period for deficits in excess of 450 mm increases from about 3 yr to 6 yr as AWC increases from 100 to 250 mm.

Table 3.18. Estimated forage water deficits (aridity indices) for zone boundaries in Fig. 3.18 for four soil AWC's and five risk levels.

Zone Boundary	Soil AWC (mm)	Water deficit				
		Probability deficit is less than amount shown				
		10%	25%	50%	75%	90%
D1-D2	100	133	185	249	319	379
	150	70	132	200	275	345
	200	21	90	159	243	313
	250	2	62	128	216	280
D2-D3	100	177	232	297	363	422
	150	115	180	250	323	389
	200	70	141	212	293	359
	250	49	113	182	266	331
D3-D4	100	220	278	344	408	465
	150	159	228	300	370	434
	200	118	192	265	342	405
	250	97	165	235	317	381
D4-D5	100	264	325	392	453	508
	150	204	276	350	418	478
	200	167	243	318	392	451
	250	144	216	289	367	432
D5-D6	100	307	371	440	497	552
	150	248	324	400	465	523
	200	216	293	371	441	497
	250	191	268	342	417	483
D6-D7	100	351	418	487	542	595
	150	293	373	450	513	567
	200	264	344	424	491	542
	250	239	319	396	467	533
D7-D8	100	395	464	535	587	638
	150	338	421	500	560	612
	200	313	395	477	541	588
	250	286	371	449	517	584
D8-D9	100	438	511	582	631	681
	150	382	469	550	608	656
	200	361	446	529	590	634
	250	334	422	503	567	634

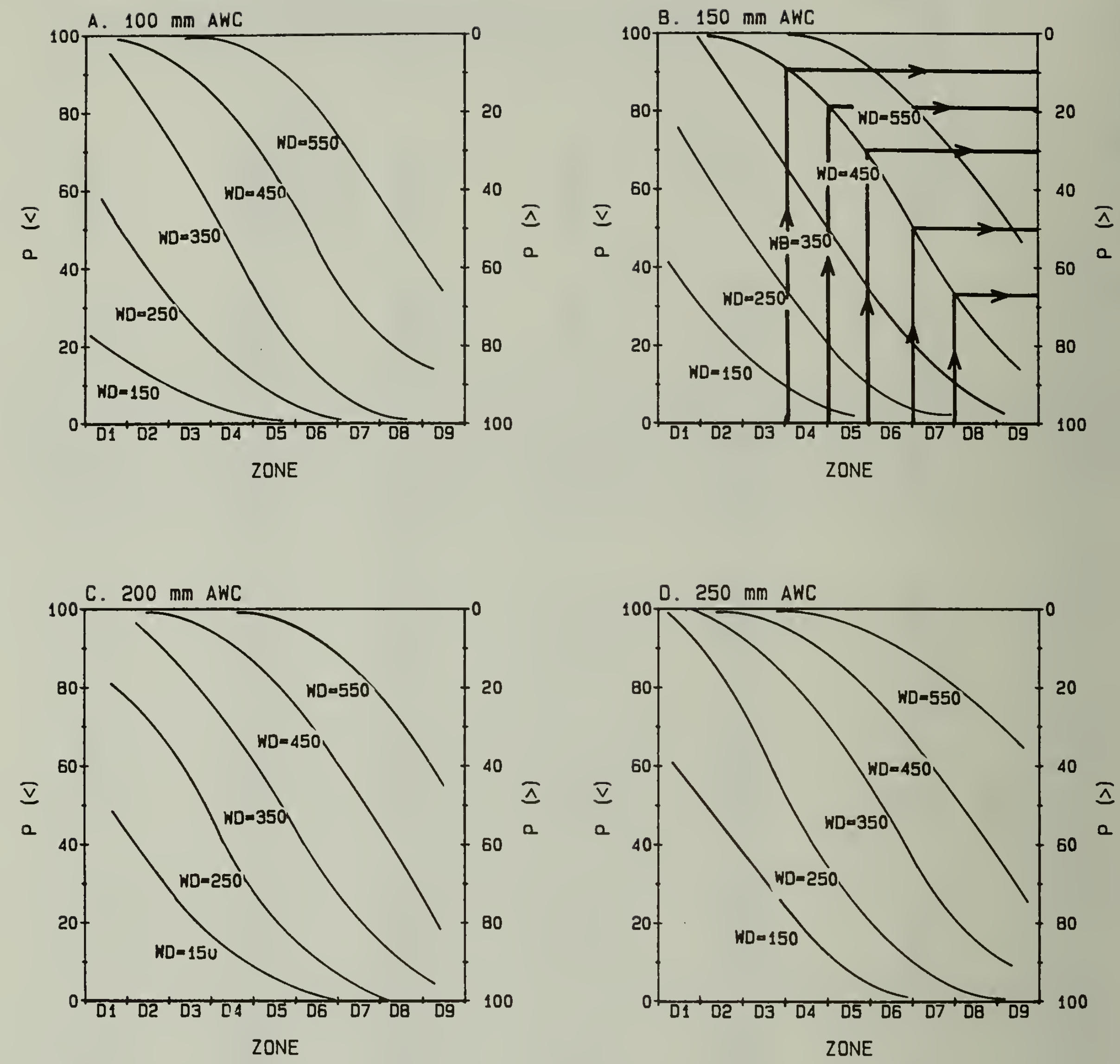


Fig. 3.19. Probability (P) that the water deficit (WD) for forages is less than (<) or greater than (>) selected thresholds for four soil AWC's (100, 150, 200 and 250 mm) in relation to zones in Fig. 3.18.

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Appendix 3.1. Risk analyses of forage water deficits : deficits at selected probability levels and probabilities at selected deficit thresholds for 27 stations.

	Forage Water Deficits not exceeded at probaility indicated (mm)																			
	Probability Level																			
	10%				25%				50%				75%				90%			
	AWC†				AWC				AWC				AWC				AWC			
Station*	100	150	200	250	100	150	200	250	100	150	200	250	100	150	200	250	100	150	200	250
SWIF	286	237	204	157	348	290	272	226	393	356	330	304	459	429	374	363	546	490	470	454
MEDI	351	315	271	267	437	378	336	336	496	455	432	400	552	515	508	485	606	567	553	560
MANY	380	338	315	289	436	399	386	363	518	479	454	440	570	541	520	494	611	581	540	569
BROO	352	278	242	238	406	376	334	310	473	420	406	380	528	492	473	444	574	528	552	516
ANER	382	328	316	290	463	405	383	351	534	482	462	441	569	552	527	512	587	590	576	567
VALM	398	346	323	303	491	452	428	408	566	554	539	495	629	609	593	575	685	666	643	611
KIND	328	290	262	251	377	344	313	284	430	399	380	343	503	465	439	407	539	521	492	510
LETH	299	198	196	168	360	321	276	240	431	396	353	328	478	447	414	396	529	490	468	429
REGI	304	252	197	171	347	295	265	252	428	390	342	324	480	456	419	396	540	522	481	468
SASK	280	222	175	136	347	304	281	250	397	362	325	302	447	406	391	356	477	446	421	400
SCOT	290	238	208	181	343	290	263	243	385	342	322	290	431	394	381	371	506	475	442	425
TUGA	300	238	182	156	375	336	312	270	452	408	371	346	491	456	437	394	550	532	468	450
HANN	262	198	171	166	307	253	233	206	354	306	294	251	443	416	374	365	509	478	471	462
MIDA	317	230	201	157	357	306	272	254	412	382	342	316	483	451	439	404	558	522	493	474
LACO	191	126	81	58	260	207	172	145	312	270	234	205	381	344	324	276	433	401	385	367
BEAV	132	77	17	14	169	136	85	58	234	198	169	126	308	279	243	221	356	325	290	266
INDI	247	171	136	132	290	240	209	176	369	332	287	251	444	407	384	361	520	473	450	437
MELF	150	87	72	56	233	181	149	134	325	276	221	194	379	348	330	286	420	394	365	330
PRIN	207	154	114	92	258	224	168	157	335	291	257	230	386	342	319	289	422	384	360	337
OLDS	128	84	32	17	200	130	118	73	260	215	168	169	327	284	252	215	355	318	290	253
BIRT	156	93	26	21	239	168	137	129	286	233	214	170	354	322	277	263	442	420	390	350
BRAN	219	165	128	73	280	220	176	145	368	308	275	239	422	396	344	323	498	473	419	406
MORD	208	126	78	61	260	175	145	117	309	261	215	194	381	330	312	286	459	420	390	354
WINN	135	48	20	15	198	151	105	73	288	240	190	150	354	298	265	250	396	368	322	287
WASK	249	179	132	81	310	264	216	173	410	362	327	296	489	450	424	398	568	539	493	483
YORK	174	119	77	49	215	181	130	98	286	230	196	154	347	290	275	257	391	362	347	307
RANF	167	126	72	39	216	176	114	95	275	238	199	171	346	308	277	247	419	392	351	321

* Only first four letters of station name are shown.

† Available soil water-holding capacity (mm).

Appendix 3.1 (cont'd.)

	Probabilities of Forage Water Deficits not being exceeded (%)																			
	AWC=100 mm					AWC=150 mm					AWC=200 mm					AWC=250 mm				
	Deficit (mm)					Deficit (mm)					Deficit (mm)					Deficit (mm)				
Station	150	250	350	450	550	150	250	350	450	550	150	250	350	450	550	150	250	350	450	550
SWIF	0.0	6.7	25.5	73.2	91.0	1.7	14.1	46.8	79.2	96.1	5.4	20.7	62.1	84.0	97.0	8.6	29.5	72.4	89.2	97.8
MEDI	0.0	0.0	9.8	28.8	74.3	0.6	3.3	19.2	47.6	85.4	1.7	6.4	26.7	62.3	89.3	2.8	7.7	29.4	67.1	89.0
MANY	0.0	1.1	4.5	27.8	64.1	0.0	3.6	12.5	31.5	79.3	2.6	4.3	15.4	48.4	93.7	2.6	4.3	22.1	54.3	87.9
BROO	0.0	4.7	9.3	34.9	79.1	0.0	5.9	18.4	61.2	93.0	1.7	11.3	29.1	63.8	89.9	1.8	12.2	39.2	77.3	93.7
ANER	0.0	2.3	5.8	19.4	60.8	0.4	3.8	11.8	39.7	74.1	2.3	4.7	15.1	45.0	82.7	2.3	5.4	24.8	53.5	86.0
VALM	0.0	0.0	3.2	20.9	41.7	0.0	0.0	11.3	24.8	47.9	0.0	2.9	14.6	26.8	55.3	0.0	3.1	17.8	32.6	65.9
KIND	0.0	1.2	16.7	63.1	91.7	0.0	3.2	27.7	69.9	97.6	2.4	6.8	37.8	80.5	99.4	1.9	9.7	53.7	76.2	100.0
LETH	0.0	6.2	22.8	59.7	94.6	1.7	11.2	36.1	76.2	100.0	5.1	16.2	47.3	84.7	100.0	6.3	26.4	60.1	92.9	100.0
REGI	0.9	3.0	26.2	59.4	90.6	3.6	9.8	38.9	72.5	92.6	5.2	20.9	52.8	83.0	93.1	6.1	24.8	57.2	86.7	95.0
SASK	0.0	6.7	25.8	76.7	100.0	2.5	14.6	46.4	91.4	100.0	5.0	20.0	60.0	96.7	100.0	11.7	25.1	72.5	99.2	100.0
SCOT	0.0	6.7	27.6	79.8	98.3	3.3	11.7	53.3	88.3	100.0	3.3	20.8	65.4	91.0	98.3	7.0	28.3	68.9	93.4	100.0
TUGA	0.0	5.0	20.0	48.3	90.0	2.9	12.9	30.0	71.2	93.2	5.9	14.7	39.4	80.8	95.8	8.3	18.3	51.7	90.0	100.0
HANN	0.0	6.6	48.2	76.4	97.9	4.3	23.4	66.0	87.2	97.9	8.5	33.1	65.8	86.5	100.0	4.4	49.1	68.3	88.4	99.8
MIDA	0.0	2.3	22.1	65.8	87.4	2.3	14.4	37.6	74.6	92.4	4.9	20.3	52.1	78.0	94.6	8.5	24.0	63.8	84.1	95.3
LACO	6.3	23.1	67.2	92.2	98.6	15.4	37.7	76.4	96.1	99.0	18.5	54.7	81.4	98.3	100.0	26.1	71.4	87.0	98.3	99.9
BEAV	16.8	58.6	87.6	100.0	100.0	31.5	64.2	97.7	100.0	100.0	41.7	78.3	99.2	100.0	100.0	56.1	84.4	100.0	100.0	100.0
INDI	1.7	11.4	39.7	77.8	96.2	5.0	27.2	56.7	86.7	99.1	13.7	35.9	68.1	90.1	99.1	17.5	49.8	71.3	91.8	98.6
MELF	10.0	30.0	61.7	95.0	98.9	16.4	39.8	75.7	96.7	100.0	25.4	59.2	86.1	96.7	100.0	33.3	61.7	96.7	100.0	100.0
PRIN	3.3	20.6	57.9	97.1	100.0	8.8	33.8	77.2	100.0	100.0	21.3	45.3	88.6	100.0	100.0	21.9	57.2	92.8	100.0	100.0
OLDS	17.9	45.8	88.2	99.6	100.0	30.1	60.6	96.7	100.0	100.0	41.4	74.4	95.0	100.0	100.0	44.3	88.5	96.7	100.0	100.0
BIRT	9.6	31.9	73.8	91.0	100.0	19.6	58.9	78.3	93.6	100.0	28.5	67.8	85.8	96.5	100.0	35.0	70.0	90.0	100.0	100.0
BRAN	1.7	17.7	46.1	79.3	99.9	6.8	34.1	60.8	88.3	100.0	17.2	43.4	79.3	95.0	100.0	26.4	52.5	85.2	96.7	100.0
MORD	4.2	21.8	69.0	88.2	98.6	16.7	45.6	78.3	93.3	98.9	27.3	65.1	84.9	95.5	100.0	34.4	67.7	88.8	98.3	100.0
WINN	11.9	37.2	73.2	97.2	100.0	24.6	53.5	86.2	100.0	100.0	40.9	71.8	94.1	100.0	100.0	50.0	75.0	98.3	100.0	100.0
WASK	3.4	10.1	36.4	65.6	87.7	3.4	22.7	46.1	75.1	91.8	12.6	30.3	56.9	80.0	96.8	22.4	35.1	63.2	82.8	100.0
YORK	6.5	35.4	76.2	97.6	99.1	15.6	60.8	87.8	97.6	100.0	32.8	68.2	90.5	97.6	100.0	48.0	73.0	94.0	97.6	100.0
RANF	6.9	39.7	76.4	96.1	100.0	15.2	58.6	85.0	98.3	100.0	33.8	69.1	89.7	98.3	100.0	41.4	75.8	94.1	98.8	100.0

Appendix 3.2(a). Regression equations used to estimate soil water content at seeding (Y) for four soil AWC's and five probability levels from the 150 mm AWC, 50% probability value (X), wheat-fallow rotation.

Probability	AWC (mm)	Regression equation	R^2	S.E. (mm)
10%	100	$Y = -105.6+4.574X -.05195X^2+.00021230X^3$	0.90	6.7
	150	$Y = -188.4+8.343X -.10505X^2+.00044730X^3$	0.87	11.3
	200	$Y = -219.8+9.930X -.11855X^2+.00049348X^3$	0.90	12.8
	250	$Y = -355.7+15.331X-.18566X^2+.00076249X^3$	0.90	16.0
25%	100	$Y = -13.0+1.012-.002369X^2$	0.95	4.2
	150	$Y = -176.3+7.796X-.09266X^2+.00038822X^3$	0.97	6.4
	200	$Y = -187.0+8.878X-.10206X^2+.00042502X^3$	0.98	6.4
	250	$Y = -323.6+14.422X-.17181X^2+.00070820X^3$	0.96	10.6
50%	100	$Y = -2556.9+13.106X-1042.24(X)^{1/2}+2530.54(X)^{1/3}$	0.97	2.1
	200	$Y = 16.0+1.2668X$	0.99	3.5
	250	$Y = -135.8+7.615X-.08450X^2+.00036545X^3$	0.98	7.2
75%	100	$Y = -2574.9+14.492X-1110.38(X)^{1/2}+2652.70(X)^{1/3}$	0.96	1.2
	150	$Y = -2949.3+13.445X-1132.67(X)^{1/2}+2812.74(X)^{1/3}$	0.97	4.0
	200	$Y = -861.7-171.60(X)^{1/2}+592.27(X)^{1/3}$	0.97	5.2
	250	$Y = -90.0+28.21(X)^{1/2}$	0.98	6.7
90%	100	$Y = -1095.5+7.069X-517.25(X)^{1/2}+1217.14(X)^{1/3}$	0.66	1.8
	150	$Y = -4774.4+25.471X-1997.42(X)^{1/2}+4811.77(X)^{1/3}$	0.91	4.3
	200	$Y = -6245.2+32.571X-2583.24(X)^{1/2}+6248.19(X)^{1/3}$	0.97	3.6
	250	$Y = -306.0-3.677X+89.22(X)^{1/2}$	0.94	8.6

R^2 = coefficient of determination
S.E. = standard error of estimate

Appendix 3.2(b). Regression equations used to estimate soil water content at seeding (Y) for four soil AWC's and five probability levels from the 150 mm AWC, 50% probability value (X), continuous wheat rotation.

Probability	AWC (mm)	Regression equation	R^2	S.E. (mm)
10%	100	$Y = -29.78+1.9000X-.023816X^2+.00011944X^3$	0.89	6.0
	150	$Y = -41.91+2.4810X-.031900X^2+.00015825X^3$	0.89	7.2
	200	$Y = -47.99+3.2874X-.041629X^2+.00020341X^3$	0.91	8.2
	250	$Y = -51.54+3.4453X-.042894X^2+.00021056X^3$	0.90	9.4
25%	100	$Y = .41+.6373X$	0.92	5.5
	150	$Y = 6.88+.4843X+.00001317X^3$	0.90	7.7
	200	$Y = -61.62+4.1925X-.050006X^2+.00023220X^3$	0.93	8.4
	250	$Y = -71.48+4.7927X-.059263X^2+.00028028X^3$	0.92	9.8
50%	100	$Y = -14.43+1.7207X-.007714X^2$	0.99	1.6
	200	$Y = -24.16+2.9784X-.028350X^2+.00013635X^3$	0.99	4.2
	250	$Y = -73.91+5.4899X-.065038X^2+.00030570X^3$	0.98	6.9
75%	100	$Y = -1174.14+6.9214X-524.888(X)^{1/2}+1252.755(X)^{1/3}$	0.90	2.9
	150	$Y = -101.39-1.2412X+34.815(X)^{1/2}$	0.95	5.5
	200	$Y = -47.74+20.641(X)^{1/2}$	0.96	6.9
	250	$Y = 24.30+1.5171X$	0.95	9.9
90%	100	$Y = -52.45-26.754(X)^{1/2}+88.258(X)^{1/3}$	0.76	2.3
	150	$Y = -533.57-130.900(X)^{1/2}+426.132(X)^{1/3}$	0.84	7.5
	200	$Y = -160.90-2.5485X+59.456(X)^{1/2}$	0.89	10.3
	250	$Y = -141.37+74.880(X)^{1/3}$	0.92	12.8

Appendix 3.2(c). Regression equations used to estimate soil water content at seeding (Y) for four soil AWC's and five probability levels from the 150 mm AWC, 50% probability value (X), fallow year, wheat-fallow rotation.

Probability	AWC (mm)	Regression equation	R^2	S.E. (mm)
10%	100	$Y = 10.01+.003363X^2$	0.87	6.4
	150	$Y = 9.64+.004035X^2$	0.86	8.1
	200	$Y = -6.88+.9111X$	0.88	10.0
	250	$Y = -14.07+1.1126X$	0.88	12.4
25%	100	$Y = -.74+.6381X$	0.93	5.2
	150	$Y = -7.12+.7853X$	0.89	8.0
	200	$Y = 2.23+1.0271X$	0.92	9.3
	250	$Y = -5.13+1.2585X$	0.94	9.5
50%	100	$Y = -14.44+1.6815X-.007378X^2$	0.99	1.9
	200	$Y = 11.02+1.2632X$	0.98	5.0
	250	$Y = 3.36+1.5314X$	0.96	9.3
75%	100	$Y = -1140.05+6.5307X-502.426(X)^{1/2}+1205.436(X)^{1/3}$	0.90	2.9
	150	$Y = -117.77-1.4052X+38.123(X)^{1/2}$	0.94	6.0
	200	$Y = -140.53-1.4244X+44.827(X)^{1/2}$	0.95	8.5
	250	$Y = -86.75+27.615(X)^{1/2}$	0.96	9.3
90%	100	$Y = -46.59-24.934(X)^{1/2}+83.049(X)^{1/3}$	0.74	2.4
	150	$Y = -565.30-136.966(X)^{1/2}+446.056(X)^{1/3}$	0.84	7.7
	200	$Y = -221.29-3.4573X+74.892(X)^{1/2}$	0.87	11.1
	250	$Y = -179.77-2.0446X+60.076(X)^{1/2}$	0.89	15.6

Appendix 3.3(a). Regression equations used to estimate soil water content at heading (Y) for four soil AWC's and five probability levels from the 150 mm AWC, 50% probability value (X), wheat-fallow rotation.

Probability	AWC (mm)	Regression equation	R^2	S.E. (mm)
10%	100	$Y = -2.38+0.2671X$	0.84	1.9
	150	$Y = 3.61-.2438X+.01108X^2$	0.90	3.8
	200	$Y = 6.07+.02312X^2-.00009369X^3$	0.94	6.0
	250	$Y = 14.94-.5547X+.03052X^2$	0.96	6.4
25%	100	$Y = -5.39+.9478X-.01807X^2+.00015547X^3$	0.91	1.8
	150	$Y = 2.55+.01488X^2-.00005981X^3$	0.96	4.4
	200	$Y = 10.40+.03790X^2-.00028152X^3$	0.95	5.7
	250	$Y = 14.18+.03433X^2-.00012434X^3$	0.96	7.1
50%	100	$Y = 6.56+.4279X$	0.89	2.5
	200	$Y = 11.31+1.6224X$	0.98	3.5
	250	$Y = -2.28+2.3368X$	0.98	6.2
75%	100	$Y = -0.37+6.58489(X)^{1/2}$	0.88	3.4
	150	$Y = 17.02+1.1106X$	0.91	5.8
	200	$Y = -74.03+52.8033(X)^{1/3}$	0.95	6.5
	250	$Y = 1774.17-26.2736X+1296.90(X)^{1/2}-2572.58(X)^{1/3}$	0.97	7.9
90%	100	$Y = 29.37+.7659X$	0.79	6.6
	150	$Y = 33.86+1.3120X$	0.84	9.5
	200	$Y = -41.06+51.471(X)^{1/3}$	0.89	9.5
	250	$Y = 1725.25-26.7130X+1274.84(X)^{1/2}-2502.40(X)^{1/3}$	0.91	12.8

Appendix 3.3(b). Regression equations used to estimate soil water content at heading (Y) for four soil AWC's and five probability levels from the 150 mm AWC, 50% probability value (X), continuous wheat rotation.

Probability	AWC (mm)	Regression equation	R^2	S.E. (mm)
10%	100	$Y = -2.84+.2643X$	0.84	1.8
	150	$Y = 2.62+.00009201(X)^3$	0.89	2.4
	200	$Y = 1.44+.4489X+.00011246(X)^3$	0.91	4.7
	250	$Y = 3.43+.4113X+.00017729(X)^3$	0.94	5.1
25%	100	$Y = -.48+.3729X$	0.92	1.8
	150	$Y = 1.84+.2803X+.00009737(X)^3$	0.94	2.9
	200	$Y = 3.37+.8047X+.00009976(X)^3$	0.94	5.0
	250	$Y = 5.80+.8024X+.00016143(X)^3$	0.94	6.0
50%	100	$Y = 5.47+.5248X$	0.91	2.6
	200	$Y = 4.44+1.6078X$	0.98	3.4
	250	$Y = -.07+2.0149X$	0.96	6.2
75%	100	$Y = -18.67-.7041X+14.545(X)^{1/2}$	0.87	4.1
	150	$Y = -15.93+12.845(X)^{1/2}$	0.91	5.8
	200	$Y = 472.81-10.1003X+434.232(X)^{1/2}-792.331(X)^{1/3}$	0.96	6.6
	250	$Y = 551.77-9.6366X+469.122(X)^{1/2}-880.858(X)^{1/3}$	0.94	9.8
90%	100	$Y = -13.52-.8301X+17.983(X)^{1/2}$	0.78	7.3
	150	$Y = -40.29+39.294(X)^{1/3}$	0.85	9.4
	200	$Y = -56.48+55.820(X)^{1/3}$	0.87	11.3
	250	$Y = -24.08+27.964(X)^{1/2}$	0.90	13.7

Appendix 3.4a. Regression equations used to estimate stress indices and water deficits for wheat (Y) from soil moisture at heading (X), 150 mm AWC, 50% probability.

Variable *	Regression equation	R^2	S.E. (mm)
Stress indices:			
Seeding to harvest (cw)	$Y = 67.26-0.6265X$	0.92	3.2
" " " (w/f)	$Y = 64.02-0.6279X$	0.93	2.8
Jointing to soft dough (cw)	$Y = 32.29-0.3936X$	0.94	1.7
" " " " (w/f)	$Y = 30.18-0.4012X$	0.96	1.4
Wheat water deficit	$Y = 329.08-3.2607X$	0.94	13.5

* cw = continuous wheat, w/f = wheat-fallow rotation

Appendix 3.4b-3.4f. Regression equations used to estimate stress indices and water deficits for wheat for four soil AWC's and five probability levels (Y) from the 150 mm AWC, 50% probability value (X).

3.4b. Stress index, seeding to harvest, wheat-fallow rotation

Probability	AWC (mm)	Regression equation	R^2	S.E. (mm)
10%	100	$Y = -1.76+.7271X$	0.94	1.9
	150	$Y = -2.24+.020986X^2-.0001591X^3$	0.92	2.9
	200	$Y = 36.74-2.9840X+.090238X^2-.0006797X^3$	0.93	2.6
	250	$Y = 37.79-3.4427X+.104520X^2-.0007951X^3$	0.93	2.9
25%	100	$Y = 6.16+.7231X$	0.96	1.6
	150	$Y = 23.63-1.6338X+.067234X^2-.0005620X^3$	0.96	2.0
	200	$Y = 25.55-1.7876X+.064987X^2-.0005028X^3$	0.96	1.9
	250	$Y = 28.63-2.4767X+.086449X^2-.0006823X^3$	0.96	2.3
50%	100	$Y = 14.86+.7404X$	0.98	1.0
	200	$Y = -3.96+.9938X$	0.99	0.8
	250	$Y = -9.67+1.1039X$	0.99	1.3
75%	100	$Y = -2.56+8.905(X)^{1/2}$	0.95	1.7
	150	$Y = -26.57+12.205(X)^{1/2}$	0.96	2.0
	200	$Y = 5.80+.9754X$	0.97	1.7
	250	$Y = -41.92+13.647(X)^{1/2}$	0.98	1.9
90%	100	$Y = 34.52+.6563X$	0.86	2.9
	150	$Y = -14.97+11.653(X)^{1/2}$	0.94	2.7
	200	$Y = 14.64+.9526X$	0.94	2.6
	250	$Y = -32.24+13.358(X)^{1/2}$	0.95	2.6

3.4c. Stress index, seeding to harvest, continuous wheat

Probability	AWC (mm)	Regression equation	R^2	S.E. (mm)
10%	100	$Y = 10.16+.009173X^2$	0.93	2.2
	150	$Y = 2.25+.010826X^2$	0.90	3.3
	200	$Y = 1.41+.010657X^2$	0.91	3.2
	250	$Y = -1.10+.011524X^2$	0.92	3.2
25%	100	$Y = 15.38+.015079X^2-.0000941X^3$	0.96	1.8
	150	$Y = 7.85+.016321X^2-.0000811X^3$	0.95	2.4
	200	$Y = 4.61+.017424X^2-.0000879X^3$	0.95	2.4
	250	$Y = -.58+.023699X^2-.0001695X^3$	0.96	2.4
50%	100	$Y = 12.02+.7792X$	0.98	1.3
	200	$Y = -3.52+1.0305X$	0.99	0.9
	250	$Y = -6.54+1.0956X$	0.99	1.3
75%	100	$Y = 23.25+.7358X$	0.96	1.7
	150	$Y = -22.39+11.627(X)^{1/2}$	0.97	1.7
	200	$Y = -29.22+12.294(X)^{1/2}$	0.97	1.7
	250	$Y = -77.68+36.805(X)^{1/3}$	0.98	1.8
90%	100	$Y = 34.57+.6397X$	0.83	3.1
	150	$Y = 26.89+.7939X$	0.88	3.3
	200	$Y = 22.78+.8393X$	0.87	3.6
	250	$Y = 18.94+.9074X$	0.88	3.6

3.4d. Stress index, jointing to soft dough, wheat-fallow rotation

Probability	AWC (mm)	Regression equation	R^2	S.E. (mm)
10%	100	$Y = -1.57+.024386X^2$	0.89	1.7
	150	$Y = -5.93+.028749X^2$	0.91	1.8
	200	$Y = -5.17+.025118X^2$	0.91	1.7
	250	$Y = -6.32+.027336X^2$	0.91	1.7
25%	100	$Y = 2.16+.4175X+.0004233X^3$	0.89	1.8
	150	$Y = -.96+.032073X^2$	0.93	1.8
	200	$Y = -1.30+.028670X^2$	0.94	1.4
	250	$Y = -2.95+.033108X^2$	0.94	1.6
50%	100	$Y = 6.90+.7076X$	0.95	1.1
	200	$Y = -1.19+.9250X$	0.99	0.7
	250	$Y = -3.87+1.0733X$	0.98	0.9
75%	100	$Y = -91.07+5.4861X-130.211(X)^{1/2}+217.456(X)^{1/3}$	0.94	1.3
	150	$Y = 0.62+.7487X+4.103(X)^{1/3}$	0.96	1.4
	200	$Y = 4.04+.9726X$	0.96	1.4
	250	$Y = 1.77+1.1026X$	0.95	1.7
90%	100	$Y = 19.44+.6084X$	0.85	1.5
	150	$Y = 5.87+.6120X+5.004(X)^{1/3}$	0.96	1.3
	200	$Y = 9.44+.9587X$	0.95	1.0
	250	$Y = 7.19+1.0645X$	0.96	1.4

3.4e. Stress index, jointing to soft dough, continuous wheat

Probability	AWC (mm)	Regression equation	R^2	S.E. (mm)
10%	100	$Y = 3.70-1.4578X+.124406X^2-.0020853X^3$	0.94	1.4
	150	$Y = -5.56+.026354X^2$	0.93	1.7
	200	$Y = -4.18+.024210X^2$	0.92	1.7
	250	$Y = -6.63+.051401X^2-.0008493X^3$	0.93	1.8
25%	100	$Y = 3.68+.022899X^2$	0.90	1.8
	150	$Y = -.32+.030229X^2$	0.93	1.9
	200	$Y = -.39+.029478X^2$	0.95	1.6
	250	$Y = -2.90+.057043X^2-.0009159X^3$	0.96	1.6
50%	100	$Y = 5.23+.7704X$	0.98	0.8
	200	$Y = -.50+.9831X$	0.99	0.7
	250	$Y = -1.36+1.0355X$	0.98	0.9
75%	100	$Y = 12.24+.7426X$	0.95	1.2
	150	$Y = -4.65+7.222(X)^{1/2}$	0.98	1.0
	200	$Y = -6.61+7.264(X)^{1/2}$	0.97	1.1
	250	$Y = -8.66+7.768(X)^{1/2}$	0.97	1.3
90%	100	$Y = 19.54+.6158X$	0.88	1.6
	150	$Y = -4.66+13.713(X)^{1/3}$	0.92	1.6
	200	$Y = 1.87+6.457(X)^{1/2}$	0.95	1.4
	250	$Y = -162.91+6.1384X-177.365(X)^{1/2}+318.168(X)^{1/3}$	0.95	1.5

3.4f. Water deficit of wheat.

Probability	AWC (mm)	Regression equation	R^2	S.E. (mm)
10%	100	$Y = 46.93+.0016551X^2$	0.88	14.0
	150	$Y = 194.41-3.1020X+.0186882X^2-.00002783X^3$	0.88	18.7
	200	$Y = 210.60-3.7159X+.0214912X^2-.00003149X^3$	0.90	18.2
	250	$Y = 269.92-5.0395X+.0291138X^2-.00004361X^3$	0.91	20.7
25%	100	$Y = 70.55+.0027612X^2-.00000323X^3$	0.97	7.6
	150	$Y = 166.76-2.0756X+.0138019X^2-.00001983X^3$	0.96	10.7
	200	$Y = 250.90-3.9032X+.0230739X^2-.00003387X^3$	0.96	12.3
	250	$Y = 166.72-3.2281X+.0218170X^2-.00003310X^3$	0.96	16.7
50%	100	$Y = 60.82+.7146X$	0.98	5.9
	200	$Y = -41.57+1.1240X$	0.99	6.4
	250	$Y = -80.67+1.3608X$	0.99	8.5
75%	100	$Y = 95.91+.7637X$	0.96	9.1
	150	$Y = 40.88+1.0610X$	0.98	9.4
	200	$Y = 231.53+1.8018X-61.089(X)^{1/3}$	0.97	12.1
	250	$Y = -40.16+1.4328X$	0.97	13.2
90%	100	$Y = 365.41+1.8926X-32.785(X)^{1/2}$	0.88	15.8
	150	$Y = 100.63+.9735X$	0.93	15.6
	200	$Y = 52.92+1.1340X$	0.95	15.4
	250	$Y = -225.78+37.000(X)^{1/2}$	0.96	14.9

Appendix 3.5a. Regression equations used to estimate thermal resources (Y) for barley (-2°C) and wheat (0°C and -2°C) from the value for barley at 0°C (X), 50% probability level.

Estimated Variable (Y) (50% probability)	Regression equation	R^2	S.E. (days)
Barley/ -2°C	$Y = 52.54-.51698X+.01451X^2$	0.87	2.5
Wheat / 0°C	$Y = -10.1+1.052X$	0.95	2.3
Wheat/ -2°C	$Y = 38.74+.00013137X^3$	0.90	2.3

3.5b. Regression equations used to estimate thermal resources for wheat and barley for 10, 25, 75 and 90% probability (Y) from 50% probability values (X).

Estimated Variable (Y)	Prob. level (%)	Regression equation	R^2	S.E. (days)
Wheat, 0°C	10	$Y = -24.77+1.2208X$	0.87	4.7
	25	$Y = -9.46+1.0432X$	0.97	1.9
	75	$Y = 10.24+.9535X$	0.96	1.9
	90	$Y = 18.18+.9466X$	0.89	3.3
Wheat, -2°C	10	$Y = -31.75+1.2950X$	0.80	4.5
	25	$Y = -10.13+1.0460X$	0.94	1.9
	75	$Y = 7.99+1.0039X$	0.91	2.2
	90	$Y = 18.16+0.9624X$	0.77	3.7
Barley, 0°C	10	$Y = -22.22+1.1347X$	0.87	4.0
	25	$Y = -11.34+1.0613X$	0.97	1.8
	75	$Y = 9.14+1.0029X$	0.94	2.4
	90	$Y = 19.72+.9599X$	0.85	3.7
Barley,-2°C	10	$Y = -19.83+1.0642X$	0.90	2.4
	25	$Y = -6.89+.9781X$	0.94	1.7
	75	$Y = 9.47+1.0033X$	0.90	2.3
	90	$Y = 19.73+.9699X$	0.80	3.4

Appendix 3.6. Regression equations used to estimate forage water deficits (Y) (aridity indices) for four soil AWC's and five probability levels from the 150 mm AWC, 50% probability value (X)

Probability	AWC (mm)	Regression equation	R^2	S.E. (mm)
10%	100	$Y = -41.08+.8711X$	0.93	22.0
	150	$Y = -108.62+.8923X$	0.90	27.7
	200	$Y = -173.25+.9718X$	0.92	27.5
	250	$Y = -187.59+.9475X$	0.89	31.3
25%	100	$Y = -0.28+.9286X$	0.97	16.5
	150	$Y = -61.38+.9645X$	0.97	16.4
	200	$Y = -113.50+1.0172X$	0.96	19.9
	250	$Y = -143.79+1.0287X$	0.95	21.6
50%	100	$Y = 58.33+.9528X$	0.99	8.9
	200	$Y = -52.03+1.0570X$	0.99	11.1
	250	$Y = -85.94+1.0702X$	0.99	11.0
75%	100	$Y = 139.87+.8933X$	0.98	11.7
	150	$Y = 85.21+.9501X$	0.98	14.2
	200	$Y = 44.24+.9930X$	0.98	13.1
	250	$Y = 15.58+1.0031X$	0.97	15.8
90%	100	$Y = 206.37+.8627X$	0.91	25.9
	150	$Y = 166.48+.8908X$	0.92	25.0
	200	$Y = 129.1+.9184X$	0.91	27.0
	250	$Y = 77.65+1.0121X$	0.91	30.6

RISK ANALYSIS OF CEREAL YIELDS IN THE CANADIAN PRAIRIES

D.W. Stewart

INTRODUCTION

The Canadian Prairies have an extremely variable climate with frequent droughts. Thus yields fluctuate widely from year to year due to weather conditions. It is necessary to take this variation into account in assessing the region's crop productivity. Average yields, while useful for some purposes, do not reflect climate variability. One way to account for this variability is to calculate cumulative probabilities of yields. This would provide a probability of a crop yielding less than or equal to a given production level.

Yields over extended time periods (40-60 years) are needed to calculate probabilities. Actual yield data are inappropriate to use, as technology and varieties change with time. One could instead use weather data only to calculate probabilities of wet and dry periods, soil water reserves or other derived indices. However, these probabilities would have to be related to yields for a regional economic assessment. To avoid these problems, one can first relate weather data to yield using a mathematical model to separate weather effects from technology time trends. This has been done for hard red spring wheat in the Canadian Prairies by Williams et al. (1975) using a linear regression model. Monthly values of precipitation and potential evaporation were related to yields using polynominal equations.

In assessing abnormal years, there are advantages in using more detailed models which incorporate aspects of the physics and physiology of growth processes and which use daily values of weather variables as inputs. In this study, a physical-based model is combined with nonlinear regression using Marquardt's algorithm (Marquardt, 1963) to separate weather effects from technology trends using data from 1961-82. The model was then used at the 1982 level of technology to calculate cumulative probabilities of yields using extended weather records (42-60 years) at selected stations. Yields of wheat are also correlated to yields of oats, barley and rapeseed so that the relevance of this probability study can be discussed for these other crops as well.

MATHEMATICAL MODEL AND TECHNOLOGICAL TRENDS

The model used in this study is described by Stewart and Dwyer (1987a). Weather inputs to the model are daily values of precipitation, maximum air temperature and minimum air temperature. Potential evapotranspiration, an important component of the model, is calculated from the air temperatures and solar radiation at the top of the atmosphere using equations of Baier and Robertson (1965), Baier (1971) and Robertson and Russelo (1968).

Model calculations start on May 1 of a given year. The method of Williams and Robertson (1965) is used to estimate soil moisture on that date for land that has been summerfallowed as well as in continuous crops. Seeding dates are estimated by calculating the soil water content of a soil surface layer of approximately 7 cm for 40 days after May 1st. Days when the soil water content of the first layer is below field capacity are counted as seeding days. Seeding is assumed to take 14 days. Mean seeding date is assumed to be the midpoint between the first and final seeding day.

Time from seeding to emergence, from emergence to heading, and from heading to maturity is calculated using the biometeorological time scale of Robertson (1968). Above ground plant dry matter and leaf area are calculated on a daily basis from emergence to maturity. Grain dry matter is calculated daily from heading to maturity, with final yield being the grain dry matter at maturity.

The model calculates both the yield of wheat seeded into summerfallow (Y_F, kg ha^{-1}) and into stubble (Y_S, kg ha^{-1}). The average yield for a given year (t) and location (j) is calculated from:

$$Y_{t,j} = a_j \, (P_j \, Y_F + (1-P_j) \, Y_S) + c_j t - c_j t^2/2T \qquad (1)$$

where P is the proportion of crop seeded into summerfallow, t is time in years, T is the total number of years in the time period minus one, a is an empirical coefficient associated with location and c is an empirical coefficient associated with time and location. Yields change with time due to such things as improved weed control, changing varieties or a degradation of soils among others. These changes with time are difficult to incorporate directly into a model and are expressed as simple empirical polynomials. The choice of the time function used here ($c_j t - c_j t^2/2T$) is discussed by Stewart and Dwyer (1987a,b).

A period from 1961 to 1982 was selected to study technological change. Sets of yield data, seeded acreages of summerfallow and stubble and weather data are needed to solve for the coefficients in the model (a's and c's plus growth coefficients associated with the model itself). Yields and acreages from 1961-1982 were obtained from Statistics Canada on a crop district basis for Saskatchewan and Manitoba and on a census division basis in Alberta. This resulted in 47 districts; 14 in Manitoba, 20 in Saskatchewan and 13 in Alberta. These districts were grouped using the map of Williams et al. (1975) into three main soil zones: Brown, Dark Brown, and Black which includes Dark Gray Chernozemic and Gray Luvisols. The Brown soil zone includes mainly Brown Chernozemic and Brown Solonetzic soils. The Dark Brown zone is mainly Dark Brown Chernozemic soils and the Black zone is Black and Dark Gray Chernozemic, Black Solonetzic and Solod, Gray Luvosolic, Regosolic, Gleysolic and Organic Great Soil Groups.

Weather data from 100 stations distributed over the 47 districts and for this same period were used. Stations within or close to a district were weighted using the Thiessen polygon method (Williams and Hayhoe, 1982) to produce a set of daily values of the weather variables for each district. Using Marquardt's algorithm (Marquardt, 1963) the model was fitted to the 22 years of data to produce a set of 47 values for the a and c coefficients. Time trends were established from the c coefficients.

Values of the location coefficient (a) and the time coefficient (c) for each crop district are listed in Table 4.1. Crop districts are numbered from one to forty-seven. The location coefficients are simple adjustment factors to deal with soil characteristics such as texture, drainage, etc., and management factors (other than the proportion of crop seeded into stubble) which vary from district to district. These values are grouped around 1.0 with almost all falling within 0.8 and 1.3, a surprisingly small range considering the many factors this coefficient encompasses. Probably this narrow range is due to the fact that a crop district is a relatively large area. Many site specific factors such as soil texture and management practices average out over large land areas.

Table 4.1. Location coefficients (a_1) and time coefficients (c_1) for each crop district. Standard errors of estimate are in brackets.

District Number		a_1	c_1
Manitoba			
1	1	0.856 (0.092)	86.59 (15.10)
2	2	0.935 (0.092)	67.76 (17.14)
3	3	0.809 (0.098)	92.58 (17.15)
4	4	0.830 (0.101)	80.69 (19.66)
5	5	0.653 (0.103)	116.28 (16.19)
6	6	0.729 (0.110)	81.84 (19.72)
7	7	0.904 (0.093)	76.15 (16.16)
8	8	0.959 (0.095)	76.90 (17.18)
9	9	0.773 (0.099)	106.54 (16.18)
10	10	1.135 (0.101)	60.95 (17.82)
11	11	1.040 (0.110)	61.07 (19.02)
12	12	0.911 (0.106)	72.01 (18.87)
13	13	1.184 (0.105)	67.12 (18.14)
14	14	0.847 (0.122)	81.28 (20.39)

Table 4.1 (Cont'd)

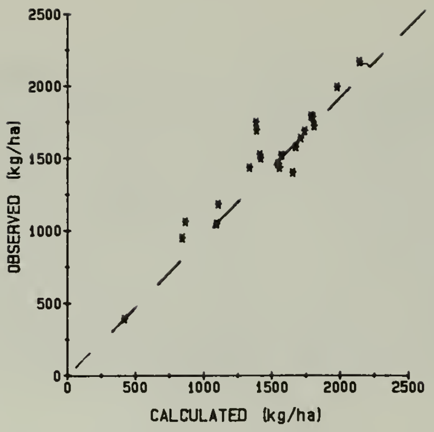
District Number		a_1	c_1
Saskatchewan			
15	1a	0.869 (0.085)	84.26 (13.58)
16	1b	1.095 (0.106)	43.53 (17.53)
17	2a	1.001 (0.073)	66.67 (11.13)
18	2b	1.203 (0.096)	64.10 (14.14)
19	3as	0.973 (0.076)	77.34 (10.91)
20	3an	0.963 (0.087)	84.90 (11.62)
21	3bs	1.089 (0.106)	70.55 (13.38)
22	3bn	0.966 (0.088)	84.08 (12.27)
23	4a	0.790 (0.098)	70.26 (13.79)
24	4b	0.967 (0.094)	83.62 (12.78)
25	5a	1.173 (0.110)	46.35 (13.58)
26	5b	1.161 (0.115)	47.76 (19.64)
27	6a	1.043 (0.099)	74.34 (14.89)
28	6b	1.040 (0.114)	80.42 (15.67)
29	7a	1.142 (0.095)	99.18 (11.64)
30	7b	1.120 (0.125)	85.97 (17.79)
31	8a	1.028 (0.126)	57.59 (21.80)
32	8b	1.129 (0.129)	84.51 (20.18)
33	9a	1.072 (0.147)	65.76 (23.90)
34	9b	0.939 (0.115)	80.62 (19.95)
Alberta			
35	1	0.883 (0.116)	93.69 (13.58)
36	2	1.111 (0.123)	119.11 (16.45)
37	3	0.932 (0.104)	90.51 (19.34)
38	4	1.031 (0.125)	60.64 (15.28)
39	5	1.190 (0.105)	77.73 (17.80)
40	6	1.286 (0.120)	35.38 (23.26)
41	7	1.297 (0.129)	24.23 (22.15)
42	8	1.045 (0.112)	69.08 (24.46)
43	10	1.138 (0.124)	67.00 (21.00)
44	11	1.192 (0.119)	66.09 (23.48)
45	12	0.596 (0.118)	118.37 (20.36)
46	13,14	0.802 (0.100)	79.13 (21.42)
47	15	0.822 (0.112)	94.67 (18.48)

The crop districts listed in Table 4.1 were grouped into 5 zones as shown in Table 4.2 where Black refers to a combined Black, Dark Gray, Gray Luvisol zone. For some comparisons all the Black zones were grouped into one to form three main zones namely Brown, Dark Brown and Black. Model calculations were plotted against actual yields for these three zones in Fig. 4.1a,b,c. Also shown are the correlation coefficients and standard errors of estimate. Note that more variation is evident in the Brown than in the darker zones, as would be expected. Not surprisingly, the model performs best in the Brown soil zone. The model concentrates on effects of soil moisture deficits on growth, with no mechanism to respond to excess moisture, which could be a factor in the darker soil zones.

Table 4.2. Grouping of crop districts (numbered in Table 4.1) into soil zones

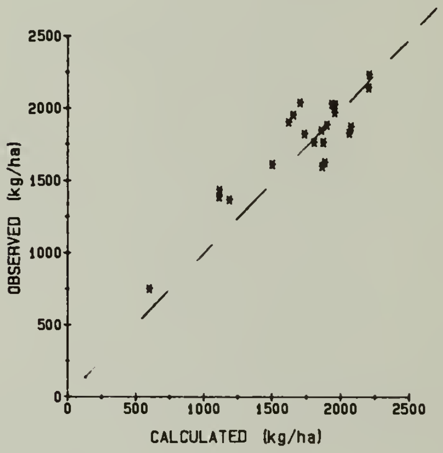
Soil Groups	Crop Districts
Brown	17, 19, 20, 21, 22, 23, 24, 29, 35, 38
Dark Brown	15, 18, 27, 28, 30, 36, 39, 41
Manitoba Black	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14
Saskatchewan Black	16, 25, 26, 31, 32, 33, 34
Alberta Black	37, 40, 42, 43, 44, 45, 46, 47

To show the technological trends, yields were calculated using equation (1) with $t=0$. Both calculated yields and actual yields were averaged by crop district for each of the three major soil zones and for each year. The differences between actual and calculated yields are shown in Fig. 4.2a,b,c. These differences increase with time because the time trend is not included in the calculations. The solid lines in Fig. 4.2 represent the time function $(ct-ct^2/2T)$ where c is averaged for each zone. Thus Fig. 4.2a,b,c shows the smoothed representation of non-weather time trends with the data from which these trends were derived. The data do show that the time function was appropriate as discussed by Stewart and Dwyer (1987b). For all zones, yields increased from 1961 to 1975 with a levelling off from 1976 to 1982.



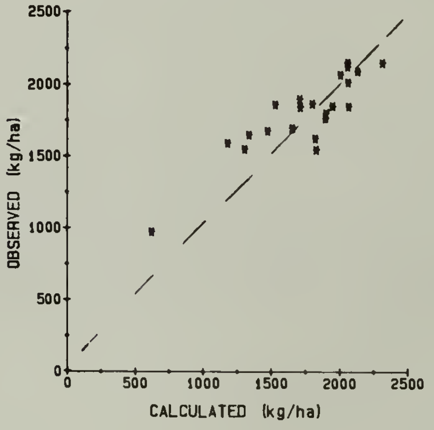
r = 0.94
SEE = 124.6 kg/ha

Fig. 4.1a: Observed versus calculated yields averaged over the Brown soil zone with the correlation coefficient (r) and standard error of estimate of the fit.



r = 0.88
SEE = 194.7 kg/ha

Fig. 4.1b: Observed versus calculated yields averaged over the Dark Brown soil zone with the correlation coefficient (r) and standard error of estimate of the fit.



r = 0.87
SEE = 209.2 kg/ha

Fig. 4.1c: Observed versus calculated yields averaged over the Black soil zone with the correlation coefficient (r) and standard error of estimate of the fit.

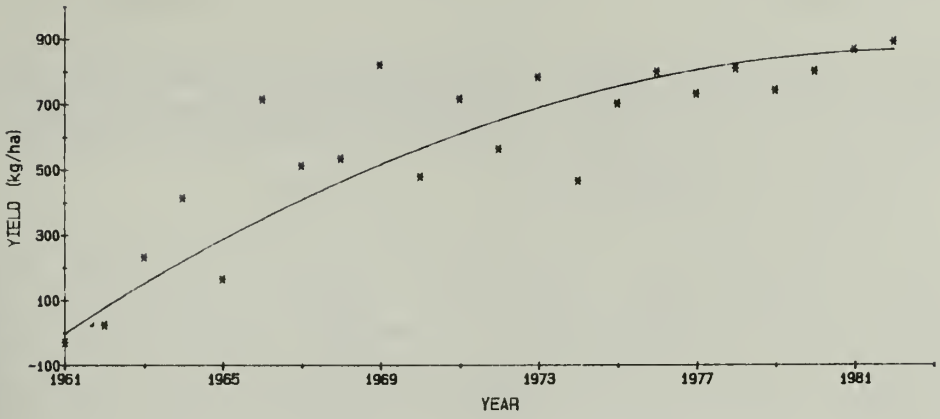


Fig. 4.2a: Difference between observed and calculated yields using equation (1) with t=0 for the Brown soil zone. The solid line is the time function $(ct-ct^2/2T)$ with c averaged for the Brown soil zone.

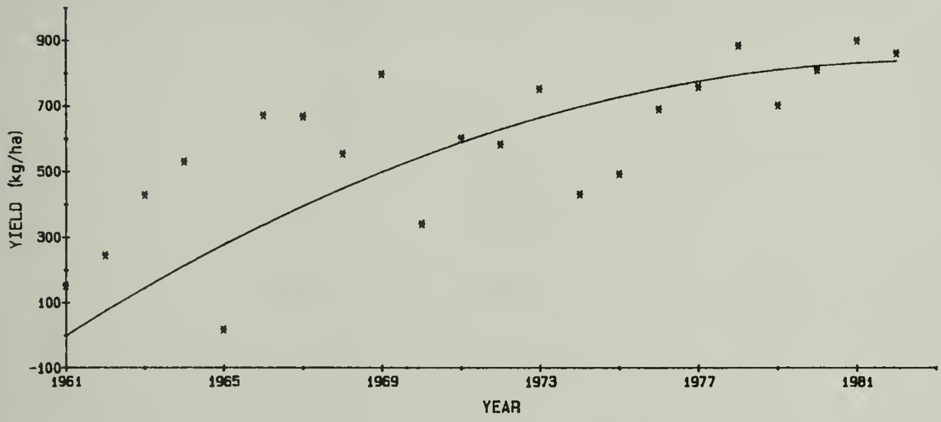


Fig. 4.2b: Difference between observed and calculated yields using equation (1) with t=0 for the Dark Brown soil zone. The solid line is the time function $(ct-ct^2/2T)$ with c averaged for the Dark Brown soil zone.

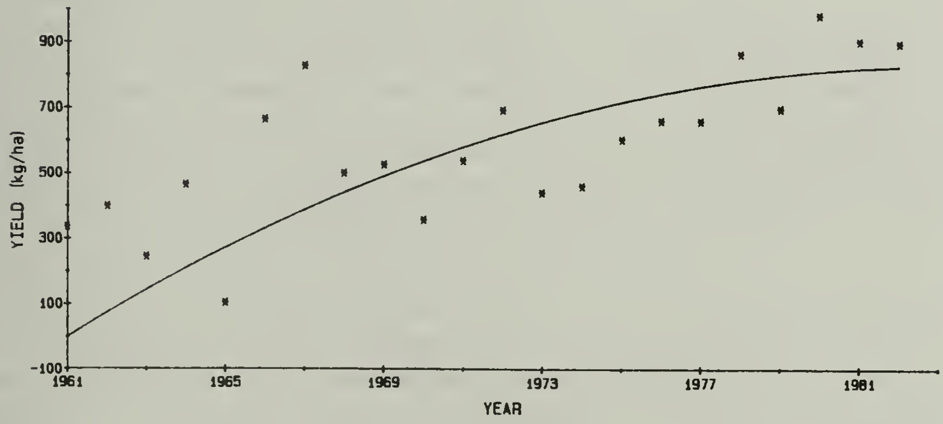


Fig. 4.2c: Difference between observed and calculated yields using equation (1) with t=0 for the Black soil zone. The solid line is the time function $(ct-ct^2/2T)$ with c averaged for the Black soil zone.

Total increase from 1961 to 1982 can be calculated from the time function with t = T = 21 years. A range of these increases can also be calculated using the standard error of the coefficient c. That is,

$$\Delta = 10.5\ (c \pm SE) \tag{2}$$

where Δ is the increase in each zone and SE is the average standard error of c for each zone. Values of Δ with its range are listed in Table 4.3. The largest yield increase occurs in the Brown followed by the Dark Brown and Black. However, differences between zones are small and all ranges overlap. Thus non-weather factors seem to be the same magnitude in all zones.

Table 4.3. Mean and range of the time trend coefficients, c and of Δ, the total calculated change in yield due to time trends

Soil Zone	Yield (kg ha^{-1}) c	 Δ
Brown	79.10±12.64	830.6±132.7
Dark Brown	76.27±16.56	800.8±173.9
Black	74.88±19.31	786.2±202.8

There are many reasons for yield increases between 1961 to 1982. Weed control, larger, more efficient machinery, new varieties and increased use of fertilizers would cause such an increase. The levelling off between 1976 to 1982 is harder to explain. Fertilizer use, for example, continued to increase during this period (Fertilizer Institute name of Canada). Decreased use of summerfallow (Table 4.4) might be thought of as a factor in this levelling off. Continuous cropping, while increasing the total production of a farm unit, tends to lower yield per seeded acreage. However changes in the use of summerfallow is not a factor in the trends indicated in Fig. 4.2. This is because the use of summerfallow via the P factor is incorporated directly in the model itself, not in the time trend function. Thus the model calculations used in Fig. 4.2, would incorporate the changes in yields with time due to changes in summerfallow. Presumably the actual yield data would also reflect these changes so that differences between actual and calculated yields would cancel any effect due to changes in summerfallow use.

Table 4.4. Values of P (proportion of land seeded into summerfallow) for each year in the three soil zones

Year	Soil zone		
	Brown	Dark Brown	Black
1961	0.85	0.78	0.58
1962	0.85	0.78	0.58
1963	0.83	0.75	0.56
1964	0.80	0.70	0.53
1965	0.85	0.75	0.57
1966	0.79	0.70	0.54
1967	0.73	0.65	0.48
1968	0.78	0.72	0.48
1969	0.86	0.83	0.62
1970	1.00	1.00	0.94
1971	1.00	0.96	0.61
1972	0.79	0.68	0.48
1973	0.83	0.74	0.50
1974	0.87	0.75	0.57
1975	0.85	0.71	0.50
1976	0.90	0.70	0.38
1977	0.83	0.82	0.52
1978	0.84	0.72	0.46
1979	0.82	0.71	0.51
1980	0.85	0.73	0.47
1981	0.78	0.65	0.36
1982	0.78	0.61	0.28

YIELD PROBABILITIES

Because yields change with time due to non-weather factors, calculations of yield probabilities should refer to current technologies and soil conditions. This can be done by using the model (equation (1)) setting t=T where T=21 years. That is, the model is set at 1982 conditions. Since non-weather yield changes approach zero in 1982, 1982 conditions will probably be appropriate today although an analysis with more recent data should be made as soon as possible.

Time periods longer than 22 years are necessary for probability calculations. Therefore 27 stations distributed over the 3 provinces were selected where records ranged in length from 42 to 60 years (see Fig. 4.3). Yields were first calculated for these time periods using equation (1) setting t=T where T=21 years. Thus for a given year i and location j, this results in

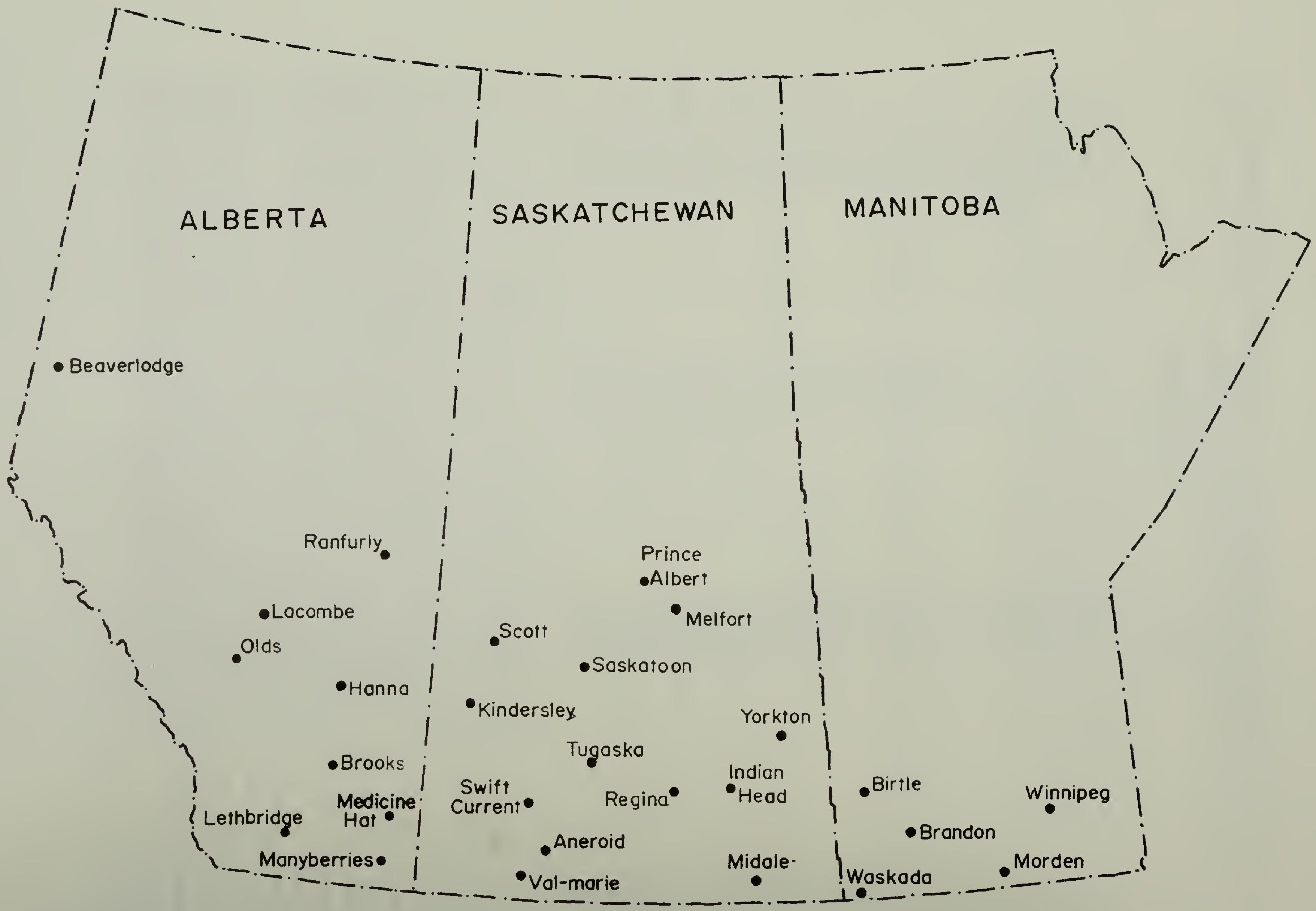


Fig. 4.3: The three prairie provinces showing the location of the 27 weather stations used in the probability calculations.

$$Y_i = a_j (\bar{P}_j Y_{Fi} + (1-\bar{P}_j) Y_{Si}) + 10.5 c_j \quad . \tag{3}$$

Values of a_j, c_j were taken from values calculated for the crop district where the weather station was located. Values of $\bar{P}_j$ were calculated by averaging P over 1980, 81 and 82 in each crop district. The problem with equation (3) is that values of Y cannot fall below 10.5 c_j, a serious limitation in dry years. Instead, the following equation was used:

$$Y_i = a_j (\bar{P}_j Y_{Fi} + (1-\bar{P}_j) Y_{Si}) Y_{M1}/Y_{M2} \tag{4}$$

where $$Y_{M1} = \sum_{i=1}^{M} a_j (\bar{P}_j Y_{Fi} + (1-\bar{P}_j) Y_{Si}) + 10.5 c_j \tag{5}$$

and $$Y_{M2} = \sum_{i=1}^{M} a_j (\bar{P}_j Y_{Fi} + (1-\bar{P}_j) Y_{Si}) \tag{6}$$

and where M is the number of years in the extended time period.

Equation (3) consists of two parts: the basic model which calculates yields at 1961 conditions, and the time trend term (10.5 c_j) which increased the calculations to 1982 conditions. To avoid using an additive term, the multiplicative term YM_1/YM_2 was developed which is an average of calculated yields at 1982 conditions divided by the average calculated yields at the 1961 conditions. If growing conditions were so severe that both YF_i and YS_i were zero, equation (2) would still give a calculated yield equal to 10.5 c_j, which is between 786 and 830 kg/ha according to Table 4.3. Equation (4), on the other hand, gives the expected value of zero. For a given location over a longer period of years, equations (3) and (4) would give the same average yield. However, over such a time sequence, extremely dry years would be encountered, and equation (4) would produce a more realistic probability distribution.

The locations of weather stations with extended records are shown in Fig. 4.3. These were grouped into the five soil zones in Table 4.5. Time sequences of yields were calculated for each equation using equation (4). Note that for a given location, yields for a crop summerfallow rotation (Y_F) and for continuous cropping were calculated (Y_S). Then they were weighted by $\bar{P}_j$ (the proportion of land seeded into

Table 4.5. Yields averaged over time with the probability of 1000 kg/ha for each weather station. Values for crops with the weighted effect of summerfallow and for continuous cropping (stubble) are given.

		WEIGHTED		STUBBLE	
Soil Zone	Station	Yield kg ha^{-1}	Prob. of 1000 kg ha^{-1}	Yield kg ha^{-1}	Prob. of 1000 kg ha^{-1}
Brown	Kindersly	1957	20.3	1364	39.3
	Swift Current	1971	14.6	1492	34.5
	Anervid	1769	25.2	1317	48.6
	Brooks	2224	12.2	1796	22.3
	Medicine Hat	2163	10.8	1709	30.8
	Manyberries	1703	18.6	1263	44.2
	Val Marie	1604	33.2	1172	53.2
		1913	19.3	1445	40.0
Dark Brown	Midale	1876	15.8	1553	28.6
	Hanna	1723	16.8	1302	41.7
	Tugaske	1963	14.1	1478	39.5
	Scott	2085	16.7	1584	24.8
	Saskatoon	1867	7.0	1390	31.8
	Regina	2012	21.3	1625	25.7
	Lethbridge	2022	9.3	1679	29.4
		1935	14.4	1516	31.6
Black Alberta	Olds	2331	4.1	2203	11.3
	Lacombe	2213	8.0	2132	7.0
	Ranfurly	2079	7.7	1833	16.8
	Beaverlodge	2116	4.4	1932	7.6
		2185	6.1	2025	10 .7
Black Sask.	Prince Albert	1905	12.3	1565	27.8
	Melfort	2169	12.4	1816	22.7
	Indian Head	2082	12.6	1750	22.2
	Yorkton	1938	16.1	1662	16.6
		2024	13.4	1698	22.3
Black Manitoba	Birtle	2133	12.1	1920	21.3
	Brandon	1989	13.9	1880	17.9
	Waskada	1904	15.6	1770	21.4
	Mordon	1949	12.3	1895	14.0
	Winnipeg	1904	5.5	1827	5.0
		1976	11.9	1858	15.9

summerfallow) and $(1-\bar{P}_j)$ respectively and then multiplied by a_j a location specific coefficient. These yields can be thought of as 'weighted' yields and will be referred to by this term.

However, there is considerable interest in probabilities of yields for continuous cropping (stubble yields). Summerfallow may contribute to soil organic matter degradation and wind erosion. However, cessation of summerfallow increases the risk of crop failures due to drought. Therefore, a quantitative assessment of these risk increases is important. To calculate stubble yields, $\bar{P}_j$ is set equal to zero in equation (3). Stubble yields calculated in this way were compared to actual stubble yields for crop districts in Saskatchewan (D.W. Stewart, unpublished study, 1985).

For each type of yield calculation (weighted and stubble), yields were ranked over each time period M in ascending order. The value for a given probability level (k) was determined as follows. The kth probability is the k (M+1)/100th observation (Anon, 1982). If this is not a whole number, a linear interpolation is made between the ranked values on either side of the observation. For example, if the 20 percent probability is the 9.5th observation, then the yield value at this probability is midway between the 9th and 10th ranked observation.

Cumulative probabilities for each station are shown in Table 4.6 for both weighted and stubble yields. Plots of cumulative probabilities for four Manitoba stations in the Black zone are shown in Fig. 4.4c,d and for four stations in the Brown soil zone are shown in Fig. 4.4a,b. The weighted and stubble yields are nearly equal in Manitoba as would be expected since $\bar{P}_j$ is quite small for crop districts in Manitoba. However, the two types of probabilities are quite different in the Brown soil zone, as summarized in Table 4.5. Average yields and the probability of obtaining 1000 kg/ha or less are tabulated by soil zone for both the weighted and stubble situation (1000 kg/ha was chosen because it is about one half the weighted yield averages). Weighted yields tend to increase with the darkness of the soil, but differences are relatively small due to the greater use of summerfallow in the lighter-coloured soil zones. Much the same can be said for the weighted probabilities. However of special interest is the very low probability (6.1%) in the Black zone of Alberta. This low probability reflects the most stable climate of the 5 zones. This is also evident from yield projections by Stewart and Dwyer (1987a).

Table 4.6. Yields at 10 levels of probabilities for the crop summer fallow rotation and continuous cropping (stubble) for each weather station.

							YIELD (kg/ha)					
							Probabilities					
Soil Group	Station	Rotation	10	20	30	40	50	60	70	80	90	99
BROWN	Swift Current	Sum. Fal.	973.6	1293.0	1526.0	1783.0	2022.0	2208.0	2388.0	2626.0	2954.0	3238.0
		Stubble	578.8	748.0	946.8	1229.0	1476.0	1650.0	1901.0	2191.0	2494.0	2956.0
	Medicine Hat	Sum. Fal.	1037.0	1198.0	1610.0	1823.0	1966.0	2356.0	2589.0	3977.0	3519.0	4480.0
		Stubble	735.7	822.4	1061.0	1253.0	1485.0	1801.0	2167.0	2423.0	3290.0	4210.0
	Manyberries*	Sum. Fal.	750.2	1059.0	1274.0	1535.0	1729.0	1795.0	1928.0	2189.0	2684.0	3765.0
		Stubble	548.2	666.8	882.3	985.5	1126.0	1229.0	1428.0	1816.0	2174.0	3658.0
	Brooks***	Sum. Fal.	984.4	1517.0	1692.0	1874.0	2150.0	2255.0	2490.0	3069.0	3846.0	4493.0
		Stubble	817.4	1031.0	1194.0	1341.0	1658.0	1861.0	2026.0	2522.0	3588.0	3855.0
	Aneroid***	Sum. Fal.	838.6	948.2	1236.0	1503.0	1765.0	1977.0	2988.0	2471.0	2713.0	3624.0
		Stubble	494.6	581.8	799.0	938.8	1164.0	1414.0	1663.0	2066.0	2442.0	3076.0
	Val Marie***	Sum. Fal.	630.1	715.5	940.8	1189.0	1589.0	1692.0	2120.0	2334.0	2711.0	4158.0
		Stubble	284.4	480.2	550.7	770.6	1079.0	1300.0	1498.0	1871.0	2338.0	3156.0
	Kindersly	Sum. Fal.	903.8	1074.0	1384.0	1795.0	2058.0	2193.0	2482.0	2594.0	3118.0	3476.0
		Stubble	678.2	798.2	928.5	1099.0	1289.0	1506.0	1614.0	1935.0	2142.0	3302.0
DARK BROWN	Lethbridge	Sum. Fal.	1140.0	1207.0	1443.0	1647.0	1896.0	2221.0	2490.0	2685.0	3323.0	3689.0
		Stubble	792.2	890.3	1107.0	1209.0	1459.0	1862.0	2157.0	2514.0	3030.0	3410.0
	Regina	Sum. Fal.	742.6	1074.0	1469.0	1790.0	2070.0	2361.0	2516.0	2806.0	3288.0	3456.0
		Stubble	416.9	769.5	1211.0	1430.0	1661.0	1784.0	2058.0	2319.0	3010.0	3148.0
	Saskatoon	Sum. Fal.	1079.0	1168.0	1492.0	1574.0	1742.0	2041.0	2131.0	2537.0	2824.0	3558.0
		Stubble	642.7	847.4	960.6	1174.0	1301.0	1484.0	1681.0	1847.0	2344.0	3413.0
	Scott	Sum. Fal.	1159.0	1332.0	1534.0	1814.0	2040.0	2236.0	2626.0	2781.0	3038.0	3728.0
		Stubble	780.7	914.3	1206.0	1292.0	1415.0	1577.0	1798.0	2309.0	2569.0	3268.0
	Tugaske	Sum. Fal.	899.1	1212.0	1459.0	1706.0	1813.0	1918.0	2341.0	2778.0	3230.0	3802.0
		Stubble	617.3	751.5	866.6	1119.0	1331.0	1559.0	1729.0	2320.0	2716.0	3554.0
	Hamna**	Sum. Fal.	941.6	1098.0	1286.0	1527.0	1771.0	1929.0	2077.0	2194.0	2794.0	3052.0
		Stubble	565.5	704.1	882.9	1189.0	1392.0	1542.0	1602.0	1700.0	2157.0	2780.0
	Midale***	Sum. Fal.	923.4	1272.0	1485.0	1629.0	1760.0	1910.0	2144.0	2564.0	3099.0	3394.0
		Stubble	602.4	815.0	1179.0	1351.0	1428.0	1609.0	1902.0	2347.0	2866.0	3032.0

Table 4.6 (Cont'd)

Soil Group	Station	Rotation	YIELD (kg/ha) Probabilities 10	20	30	40	50	60	70	80	90	99
BLACK ALBERTA	Lacombe	Sum. Fal.	1297.0	1535.0	1708.0	1858.0	2133.0	2403.0	2628.0	3025.0	3232.0	4174.0
		Stubble	1172.0	1463.0	1612.0	1794.0	2046.0	2301.0	2542.0	2967.0	3180.0	4119.0
	Olds	Sum. Fal.	1278.0	1665.0	1979.0	2087.0	2373.0	2630.0	2855.0	3002.0	3168.0	3564.0
		Stubble	1147.0	1602.0	1788.0	2010.0	2319.0	2458.0	2669.0	2849.0	3113.0	3493.0
	Ranfarly	Sum. Fal.	1131.0	1399.0	1527.0	1898.0	2048.0	2274.0	2492.0	2815.0	3074.0	3806.0
		Stubble	902.8	1025.0	1340.0	1591.0	1832.0	1944.0	2061.0	2726.0	3016.0	3567.0
	Beaverlodge	Sum. Fal.	1246.0	1526.0	1649.0	1856.0	2196.0	2409.0	2536.0	2703.0	2842.0	3390.0
		Stubble	1112.0	1306.0	1507.0	1689.0	1857.0	2145.0	2335.0	2550.0	2690.0	3274.0
BLACK SASK.	Indian Head	Sum. Fal.	966.2	1257.0	1601.0	1735.0	2018.0	2367.0	2667.0	2898.0	3208.0	3622.0
		Stubble	504.3	975.0	1212.0	1430.0	1701.0	1841.0	2405.0	2686.0	3038.0	3564.0
	Melfort	Sum. Fal.	951.8	1352.0	1668.0	2065.0	2300.0	2437.0	2585.0	2947.0	3088.0	3856.0
		Stubble	714.2	979.7	1333.0	1560.0	1873.0	2145.0	2299.0	2528.0	2847.0	3557.0
	Prince Albert	Sum. Fal.	958.0	1134.0	1506.0	1731.0	1945.0	2158.0	2311.0	2545.0	2791.0	3397.0
		Stubble	728.6	858.8	1125.0	1373.0	1526.0	1768.0	1954.0	2112.0	2454.0	3040.0
	Yorkton***	Sum. Fal.	855.5	1456.0	1681.0	1814.0	1947.0	2021.0	2338.0	2929.0	2812.0	3131.0
		Stubble	616.4	1129.0	1377.0	1505.0	1589.0	1804.0	1931.0	2399.0	2644.0	2862.0
BLACK	Birtle	Sum. Fal.	907.9	1395.0	1675.0	2146.0	2269.0	2423.0	2540.0	2839.0	3061.0	4051.0
		Stubble	669.4	1090.0	1469.0	1945.0	2042.0	2245.0	2360.0	2626.0	2906.0	3848.0
	Brandon	Sum. Fal.	929.8	1300.0	1625.0	1868.0	2022.0	2242.0	2486.0	2605.0	2902.0	3634.0
		Stubble	822.4	1253.0	1507.0	1743.0	1831.0	2170.0	2360.0	2508.0	2763.0	3543.0
	Morden	Sum. Fal.	935.6	1436.0	1602.0	1882.0	2092.0	2202.0	2306.0	2508.0	2821.0	3068.0
		Stubble	845.1	1349.0	1546.0	1833.0	2018.0	2187.0	2283,0	2483.0	2792.0	3030.0
	Waskada	Sum. Fal.	763.5	1236.0	1419.0	1649.0	1989.0	2211.0	24440.0	2624.0	2986.0	3678.0
		Stubble	612.5	1076.0	1267.0	1542.0	1805.0	2042.0	2230.0	2507.0	2914.0	3468.0
	Winnipeg	Sum. Fal.	1250.0	1376.0	1602.0	1699.0	1916.0	2002.0	2340.0	2406.0	2645.0	3022.0
		Stubble	1113.0	1248.0	1508.0	1655.0	1843.0	1928.0	2244.0	2391.0	2574.0	2986.0

* 55
** 47
*** 42

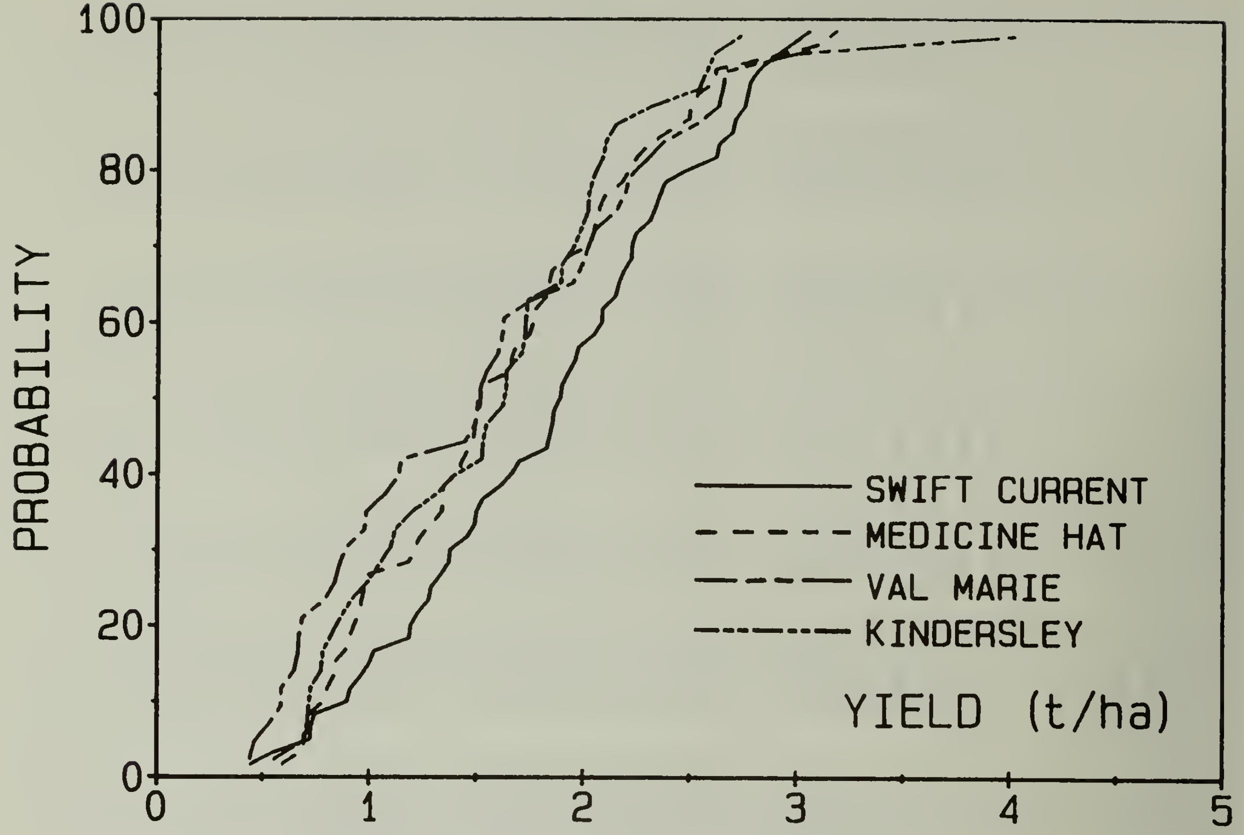


Fig. 4.4a: Cumulative probabilities for weighted yields for four stations in the Brown soil zone.

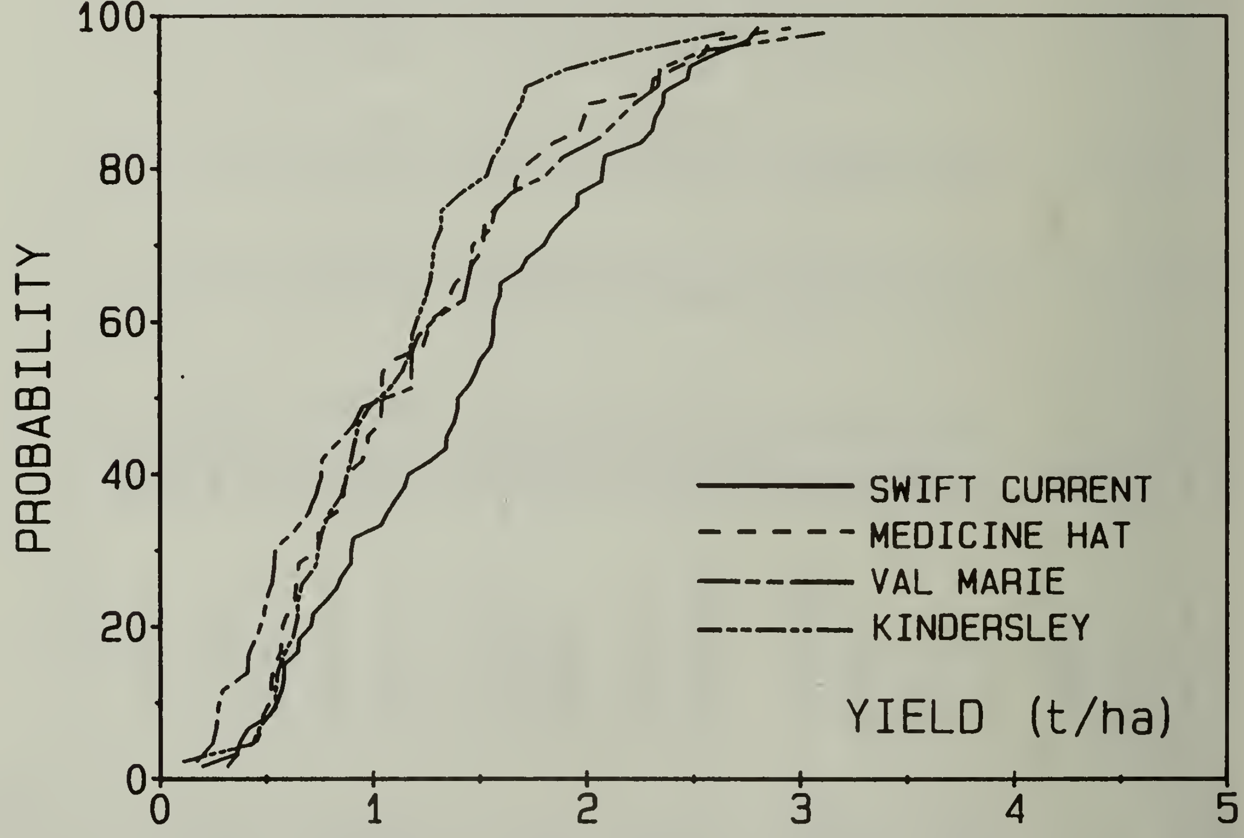


Fig. 4.4b: Cumulative probabilities for stubble yields for four stations in the Brown soil zone.

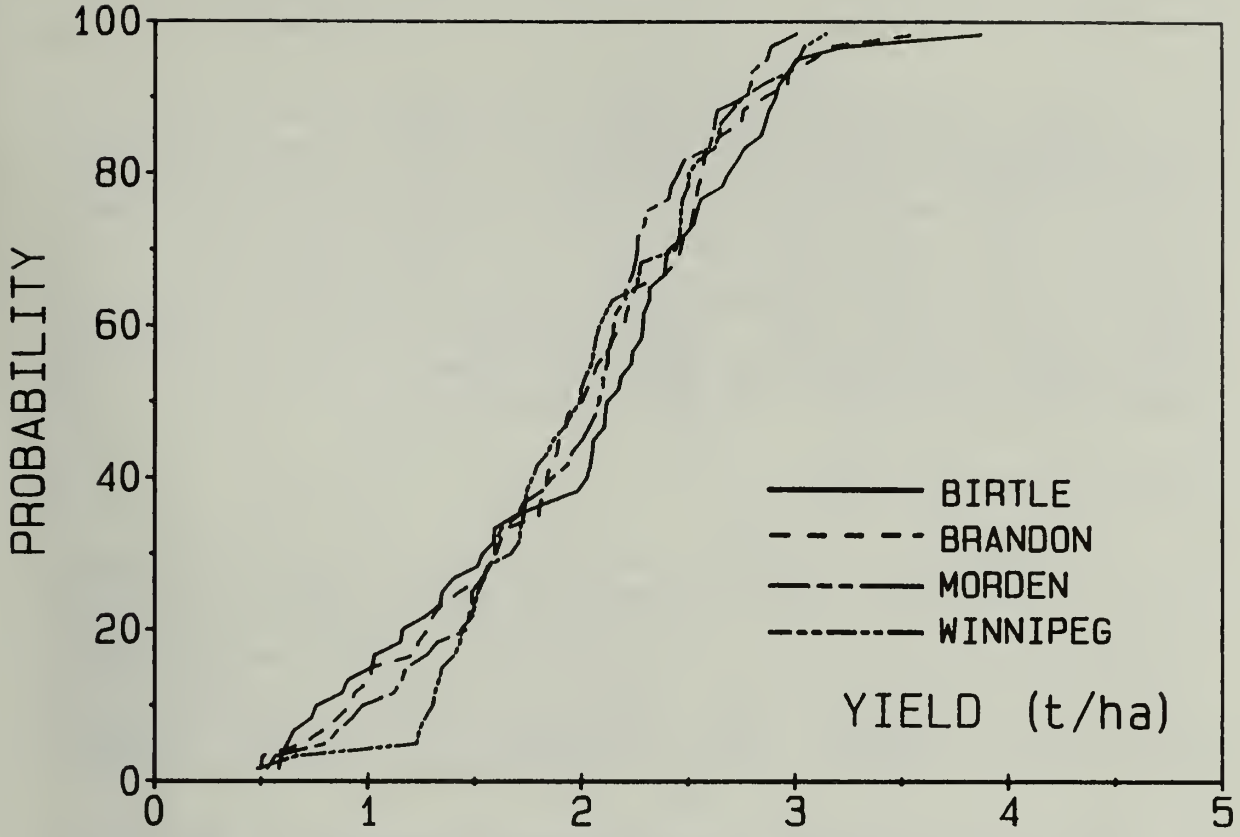


Fig. 4.4c: Cumulative probabilities for weighted yields for four stations in the Black soil zone in Manitoba.

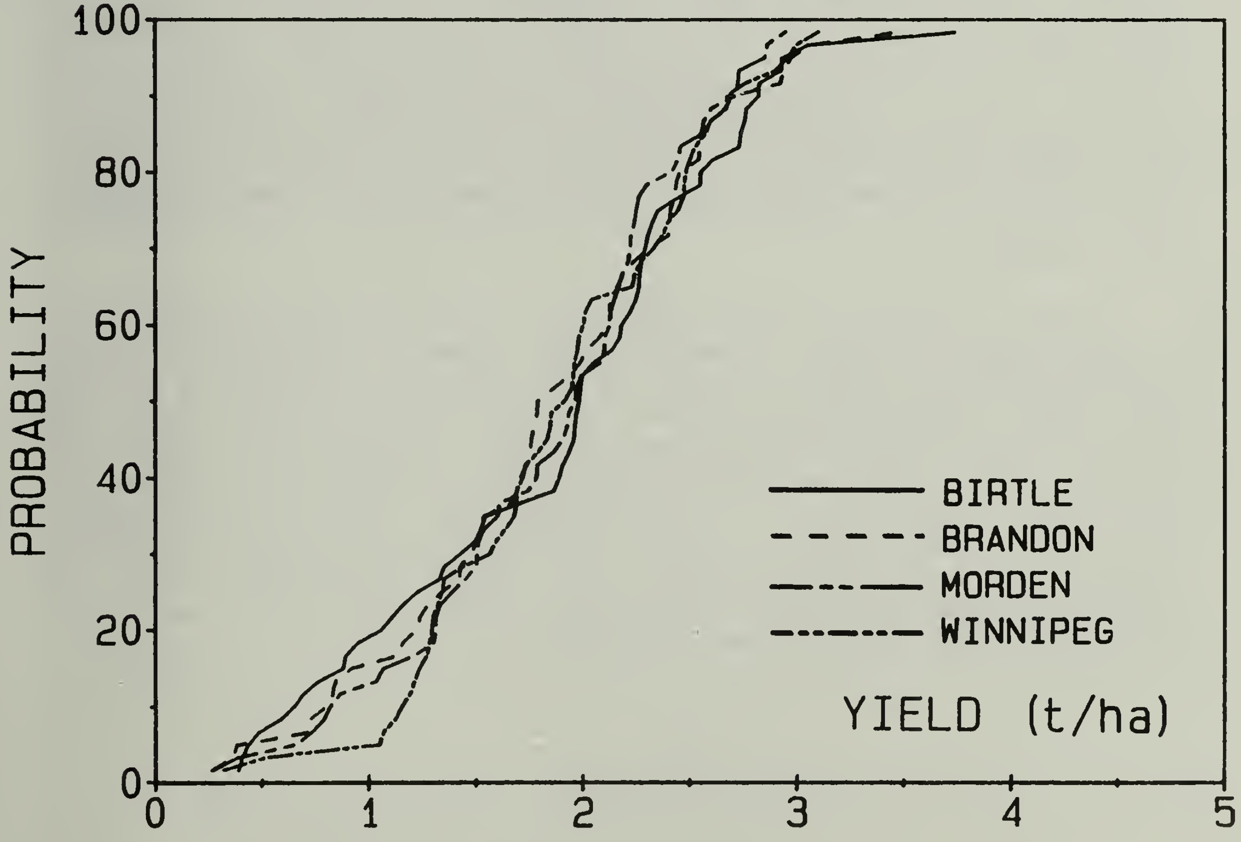


Fig. 4.4d: Cumulative probabilities for stubble yields for four stations in the Black soil zone in Manitoba.

Larger differences between zones are evident in the calculations for stubble in Table 4.6. The reason for a summerfallow crop rotation is to decrease the risk of crop failure. Thus it is not surprising that the 1000 kg/ha probabilities double with continuous cropping. However they are much lower in absolute terms in the Black soil zones. It's probable that a farmer could tolerate a 10 to 15% probability of a 1000 kg/ha yield as in Black Alberta and Manitoba but not 30-40% as in the Brown and Dark Brown zones. Black Saskatchewan at 22% is in between. This high value for a Black zone is reflected in the greater use of summerfallow in the Black zone of Saskatchewan.

TIME SEQUENCES OF YIELDS

The same yields that were used for probability calculations were plotted against time for both weighted and stubble cases for the 5 soil zones in Fig. 4.5a,b,c,d,e. Five year moving averages are also shown. A yield calculation for a given year integrates various weather factors into one value (in this case 2 values if the stubble situation is also calculated). Thus these yield sequences in time are a useful way to study trends in weather. Note that technological change isn't a factor here since all calculations are done at the 1982 level of technology.

There are a number of interesting phenomena in these time sequences. The influence of the droughts in the 30's, early 60's and to a lesser extent the early 80's are evident. The early 30's drought was most severe in the Brown and Dark Brown zones and least severe in the Black zones of Alberta and Saskatchewan. The relative stability of yields in the Black zone of Alberta is quite evident. There is also a lack of any clear time trend in yields in these graphs, indicating that the climate does not seem to be changing to increase or decrease yields. There does seem to be a tendency from 1966 onward for a reduced variability in yields. The period for 1966 to 82 seemed to have relatively stable weather.

However, the most interesting aspect of these time sequences is a tendency toward cycles. These are most evident in the Black soil zone of Saskatchewan. Droughts occur in the late 30's early 60's and the early 80's reflecting a 18-22 year cycle. Cycles of this length were also observed by Currie and Hameed (1986) for corn yield in Iowa and Illinois, USA. The early 30's drought most evident in the Brown and Dark Brown zones do not fit into this pattern. Studies are underway to objectively measure these cycles using spectral analysis. The above procedure for calculating probabilities assumed that weather events are not related from one year to the next. Presence of cycles would mean that probability distributions would change with time.

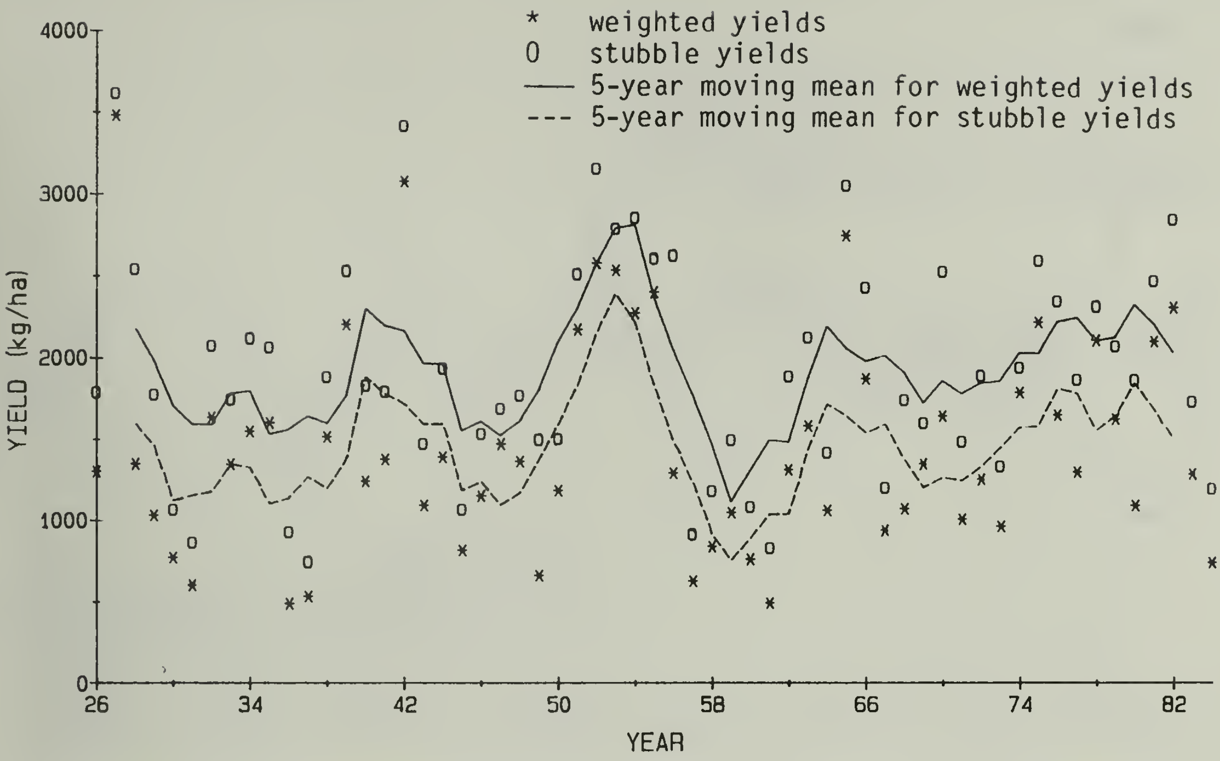


Fig. 4.5a: Time sequences of yields over 60 years for the Brown soil zone.

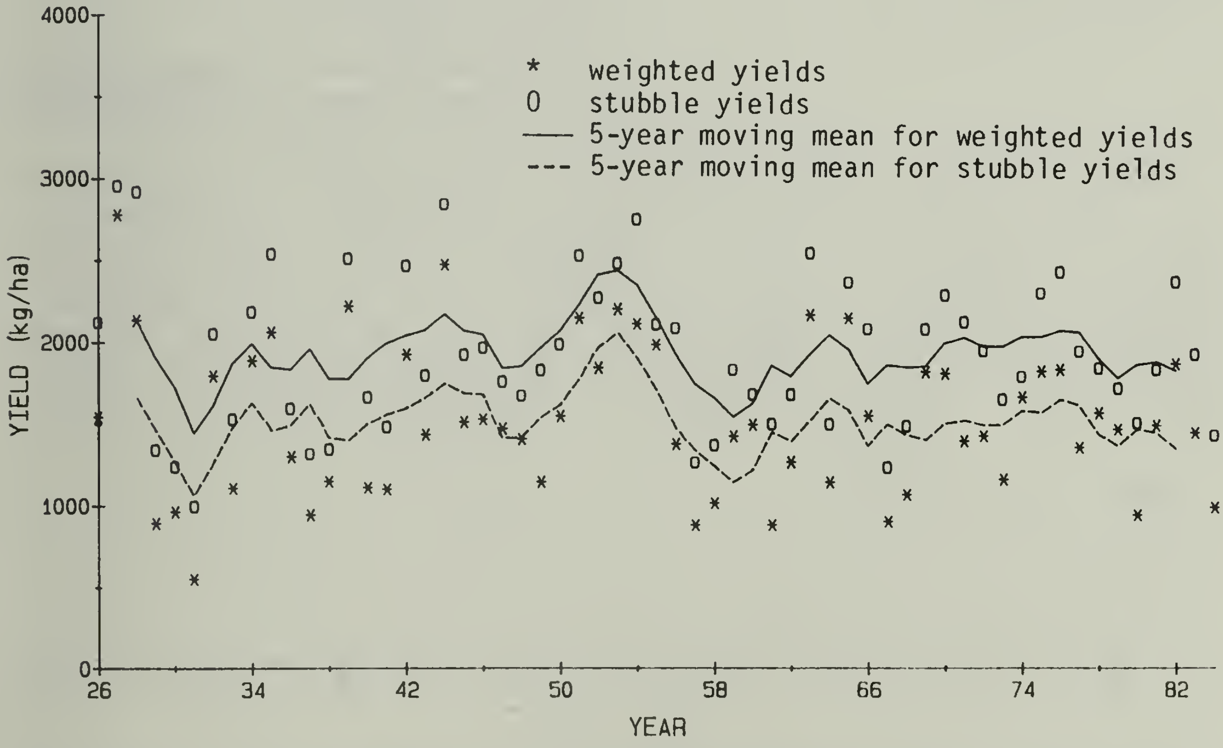


Fig. 4.5b: Time sequences of yields over 60 years for the Dark Brown soil zone.

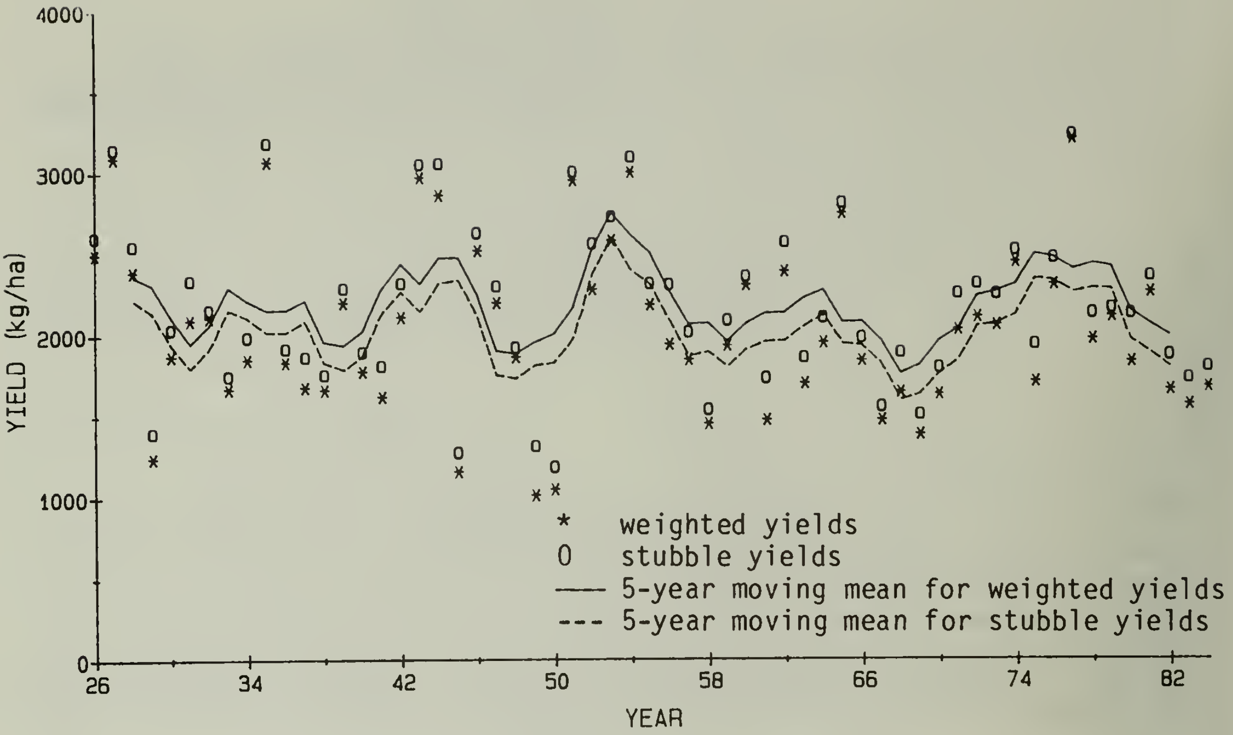


Fig. 4.5c: Time sequences of yields over 60 years for the Black soil zone in Alberta.

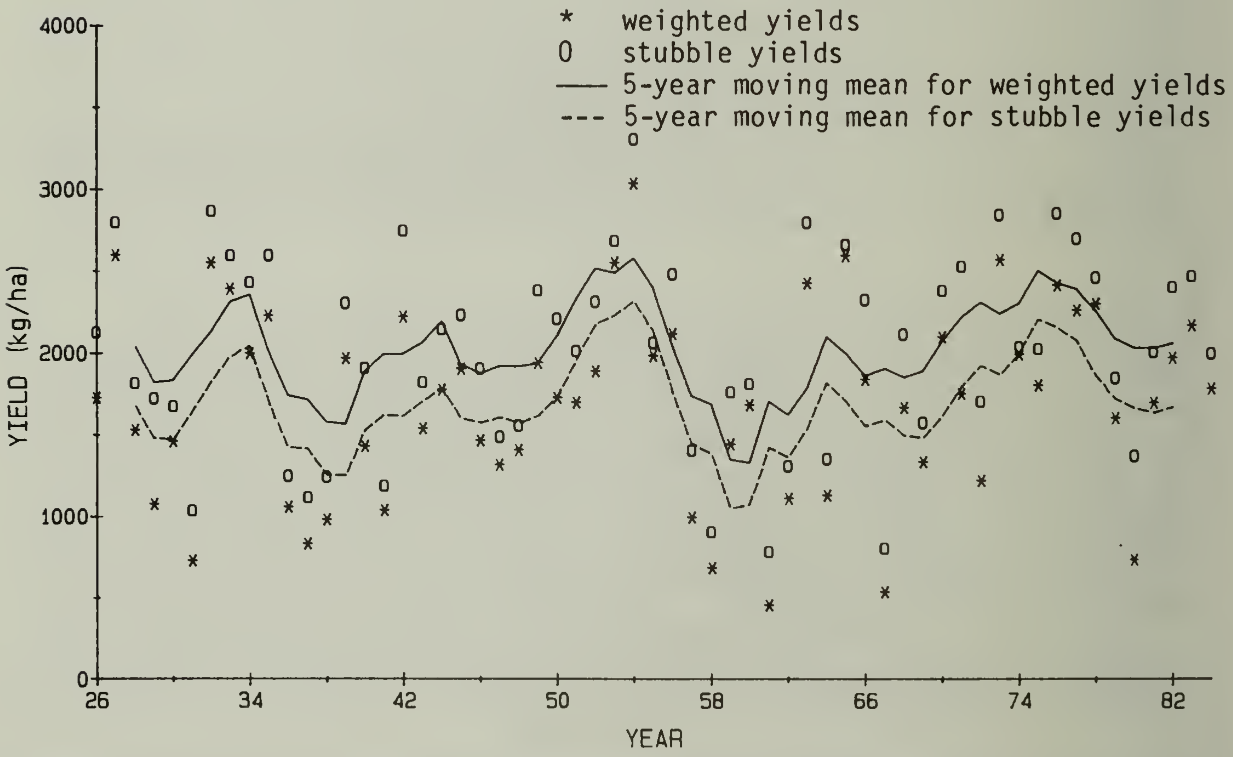


Fig. 4.5d: Time sequences of yields over 60 years for the Black soil zone in Saskatchewan.

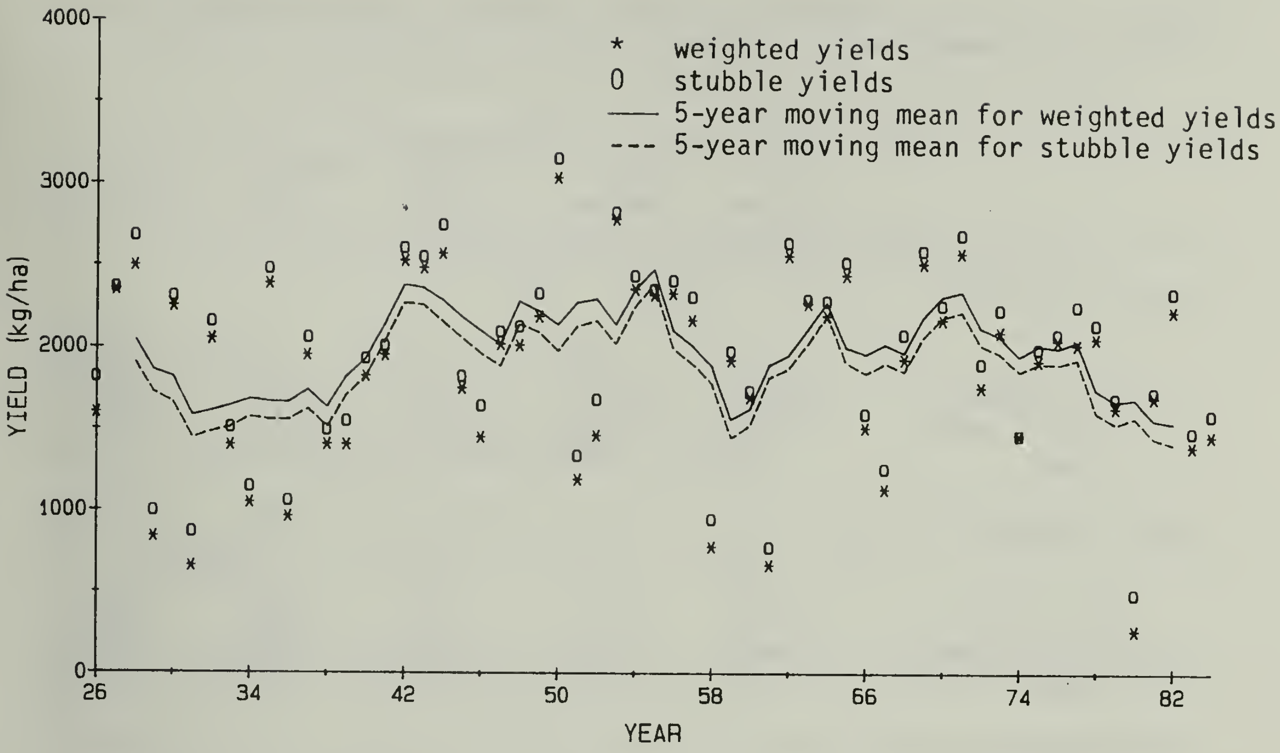


Fig. 4.5e: Time sequences of yields for 60 years for the Black soil zone in Manitoba.

OTHER CROPS

Up to this point discussion has been confined to yields of hard spring wheat. However, oats, barley and canola are also important crops in the prairies. Results of relating yields of these crops to wheat are shown in Table 4.7 for the 5 zones. For oats and barley, correlation coefficients are 0.9 or greater for all zones. Thus by using the Y intercept and slope yields, of wheat can easily be converted to yields of oats and barley and probabilities calculated. However, correlations with canola are relatively low (0.43 to 0.63). Thus a separate model with a new analysis will have to be developed for canola.

Table 4.7. The relationship of barley, oat and canola yields to spring wheat.

	Soil Zones				
	Brown	Dark Brown	Black Alta	Black Sask	Black Manitoba
Barley (1961-83)					
r	0.98	0.96	0.96	0.96	0.93
SEE (kg/ha)	106.3	120.7	101.9	128.6	172.5
Y Int kg/ha	86.0	-99.10	-114.5	-254.2	-218.6
Slope	1.22	1.30	121.5	1.34	1.27
Oats (1961-83)					
r	0.96	0.95	0.95	0.94	0.90
SEE (kg/ha)	107.3	107.7	99.2	122.0	144.4
Y Int (kg/ha)	245.8	80.1	103.3	-45.6	172.0
Slope	0.95	1.033	0.97	1.06	0.90
Canola (1967-83)*					
r	0.63	0.43		0.56	
SEE (kg/ha)	164.5	147.6		159.0	
Y Int (kg/ha)	328.2	574.1		360.0	
Slope	0.50	0.344		0.48	

* for Saskatchewan only.

CONCLUSIONS

(a) Yields can change with time due to both weather and non-weather factors, and these effects can be separated and thus clarified using a mathematical model.

(b) Yields have increased from 1961 to 1975 with a levelling off from 1976 to 1982.

(c) These yield increases are very similar for the different soil zones in the prairie provinces and are approximately 800 kg/ha over the 22 years.

(d) Probabilities of yields tend to be similar from zone to zone because the increased risk of droughts in the light-coloured soil zones is compensated for by the increased use of summerfallow.

(e) The probabilities of yields for continuous cropping varies markedly between zones.

(f) Variability of weather changes with zones. Highest variability is in the Brown while the least is in the Black zone of Alberta.

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ASSESSING THE PHYSICAL LAND FLEXIBILITY OF THE PRAIRIE REGION OF WESTERN CANADA

J. Dumanski, Z.Y. Zeng and V. Kirkwood

INTRODUCTION

The range of climates and diversity of soils in the prairie region of western Canada, results in a variety of land use possibilites in this region. This diversity of production environments enhances the economic viability of certain areas relative to others. General yield levels and long term yield reliability vary from area to area, and both are important when considering strategies for minimizing or managing production risk. Earlier studies have shown that farmers have adjusted their farming systems to capitalize on this diversity (Dumanski et al., 1982; 1987), probably in an effort to reduce operating costs, maximize efficiency and enhance their ability to withstand periods of climatologic and economic stress.

This being the case, estimates of land use flexibility can be useful indicators of agricultural opportunity. Regions with high flexibility would provide the highest opportunity for crop diversity, the highest probability for land use adjustment in response to external stress, and the highest liklihood for long term income stability under variable conditions. Areas with low flexibility have minimal opportunities for land use adjustment and often are the first to suffer during periods of environmental stress due to factors such as droughts, or economic stress due to low prices or market instability. The problem, however, is how should land use flexibility be measured? This paper examines some of the underlying concepts behind land use flexibility, and describes some procedures for deriving such estimates.

Land use flexibility is often conceptually equated with economic viability, but for practical purposes it is best to keep these concepts separate. Flexibility, as used in this report is a physical land variable that describes the opportunity for land use diversity or the possibility for land use adjustment*. Viability on the other hand relates to the way land is managed (and to associated costs and returns) and it is an economic variable. Any land use in any area with any degree of flexibility can be economically viable, if the rate of return exceeds the costs of operation.

Flexibility, in the socio-economic sense, has been studied by using optimizing programming techniques to search for a range of feasible solutions. Chang et al. (1982) utilized optimizing techniques to generate sets of feasible solutions, maximally different from each other, but within a specified set of biophysical and socio-economic resource constraints. Chapman et al. (1984), on the other hand, evaluated flexibility in resource use by studying sets of feasible resource allocations for a particular scenario, compared to those from a base scenario. This demonstrates that "flexibility" is somewhat of an abstract concept, often related to types of data used in the analyses.

* Physical land flexibility incorporates the concept of land use flexibility, and it can only be described in terms of the land uses being considered. When crop yields are used in the calculations, then some aspects of economic flexibility are also incorporated in the concept.

In this study, land use flexibility was handled only in the physical sense. Thus, it is related to the number of crops that could be grown to maturity in an area, the suitability of the climate and soils for production of the crops, and the yields that could be expected. Evaluations were made for individual areas and analysed geographically, using map unit areas (polygons) and data from the Land Potential Data Base (Kirkwood et al., 1982). This is a computerized integrated, soil, climate, land use and crop yield data base, constructed on the basis of the polygons in the Soils of Canada map (Clayton et al., 1977). Three procedures were employed for evaluating flexibility, as described below. The evaluations apply only to rainfed agriculture.

Land Use Flexibility Related to Soil and Climate Suitability

Land use flexibility can be estimated through evaluations of the natural constraints of soil and climate. Thus, an area that is judged to be suited for several crops, has a higher degree of flexibility than one that is suited for only a few crops.

The Land Potential Data Base (LPDB) includes estimates of soil and climate suitability (well suited, suited, not suited) for the eight crops* utilized in this study (spring wheat, corn, soybean, phaseolus bean, barley, oats, canola, sunflower). The criteria for constructing these tables are shown in Table 5.1. The number of crops per map unit area, well suited or suited, were simply tallied and plotted geographically, with no discrimination on expected yield or the portion of the area suitable for the crop. Results are shown in Fig. 5.1.

This illustrates what has been intuitively known for many years, that on the basis of soil and climate suitability alone, southern Manitoba has the highest potential for crop diversification in the prairie region. All or most of the crops included in this study can be grown successfully in some parts of that area. This is followed closely by east-central Saskatchewan where six of the original eight crops are suitable (corn and soybeans drop out). Certain isolated areas are suitable for five crops, generally the cereals, canola and phaseolus bean, but the largest part of the remainder of the prairie region is suitable for only four of the eight crops used in this study. The northern and western subhumid and humid areas are suitable for cereals and canola, whereas the remaining areas in the south are suitable only for cereals. It should be emphasized that not withstanding the suitability groupings developed, considerable variation can be expected within any category.

Physical Land Flexibility Related to Soil and Climate Suitability and Potential Yields.

An assessment of the suitability of a soil for a crop (or a group of crops) in a given area is only a partial answer to the question of land use

* Soil and climate suitability is also available for potato. However, root and tuber crops were not included in this analyses, because yields of these crops are disproportionate to the other crops in the study. Data for other crops, such as flax, winter wheat, lentils and the various forages, are not available in the Land Potential Data Base.

Table 5.1. Criteria for Estimating Soil and Climate Suitability in the Prairie Region Using Information from the Soils of Canada Map.

Crop	Corn Heat Units	Growing Season	Capability Class		Soil Profile Criteria		Soil Phase Criteria
			Well suited	Suited	Well suited	Suited	
Corn	≥2300	>130 days	1,2	3	Humic Gleysol	Black Chernozemic (Subhumid) Solod (Humid) Orthic Gleysol Dystric Brunisol Regosol (Humid)	1. Downgrade one class for strongly calcareous 2. Very strongly calcareous, not suited 3. Downgrade one class for sandy texture
Soybean	≥2200		1,2	3	Humic Gleysol	Orthic Gleysol Podzol	Same as corn
Phaseolus bean		1000 deg days >5°C	1,2	3	Eutric Brunisol Podzol (Humid)	Black Chernozemic (Subhumid) Dark Gray Chernozemic (Subhumid) Humic Gleysol Dystric Brunisol Regosol (Humid)	1. Downgrade one class for strongly calcareous 2. Very strongly calcareous, not suited 3. Rolling and strongly rolling topography not suited
Wheat		1000 deg days >5°C	1,2	3,4	Dark Brown Chernozemic Black Chernozemic Dark Gray Chernozemic All Solods except Brown Eutric Brunisol	Brown Chernozemic All Solonetz Gray Luvisol Humic Gleysol Dystric Brunisol Cumulic Regosol	

Table 5.1. Criteria for Estimating Soil and Climate Suitability in the Prairie Region Using Information from the Soils of Canada Map (Continued)

Crop	Corn Heat Units	Growing Season	Capability Class Well suited	Capability Class Suited	Soil Profile Criteria Well suited	Soil Profile Criteria Suited	Soil Phase Criteria
Barley			1,2,3	4	Black Chernozemic Dark Gray Chernozemic Black Solod Dark Gray Solod	Dark Brown Chernozemic Brown Chernozemic Black Solod Podzol Cumulic Regosol Humic Gleysol Eluviated Gleysol Orthic Gleysol Orthic Gray Luvisol Eutric Brunisol Dystric Brunisol	1. Very strongly calcareous, downgrade one class 2. Sandy texture, downgrade one class except for Podzols and Brunisols 3. Clayey texture, upgrade one class except for Gleysols, and Podzols
Oats			1,2,3	4	Black Chernozemic Dark Gray Chernozemic Black Solod Dark Gray Solod	Dark Brown Chernozemic Brown Chernozemic Black Solod Cumulic Regosol Humic Gleysol Eluviated Gleysol Orthic Gleysol Gray Luvisol Eutric Brunisol Dystric Brunisol	1. Very strongly calcareous, not suited 2. Strongly calcareous, reduce one class

Table 5.1. Criteria for Estimating Soil and Climate Suitability in the Prairie Region Using Information from the Soils of Canada Map (Concluded)

Crop	Corn Heat Units	Growing Season	Capability Class		Soil Profile Criteria		Soil Phase Criteria
			Well suited	Suited	Well suited	Suited	
Canola			1,2	3,4	Black Chernozemic Dark Gray Chernozemic Black Solod Dark Gray Solod	Dark Brown Chernozemic Brown Chernozemic Black Solod Podzol Cumulic Regosol Orthic Humic Gleysol Humic Eluviated Gleysol Orthic Gleysol Gray Luvisol Eutric Brunisol Dystric Brunisol	1. Very strongly calcareous, downgrade one class 2. Sandy texture, downgrade one class except for Podzols and 3. Brunisols Clayey texture, upgrade one class except for Gleysols, and Podzols
Sunflower			1,2	3	Black Chernozemic	Dark Brown Chernozemic Black Solod Cumulic Regosol Orthic Humic Gleysol Humic Eluviated Gleysol Orthic Gleysol Eutric Brunisol	1. Very strongly calcareous, not suited 2. Strongly calcareous, downgrade one class 3. Sandy texture downgrade one class

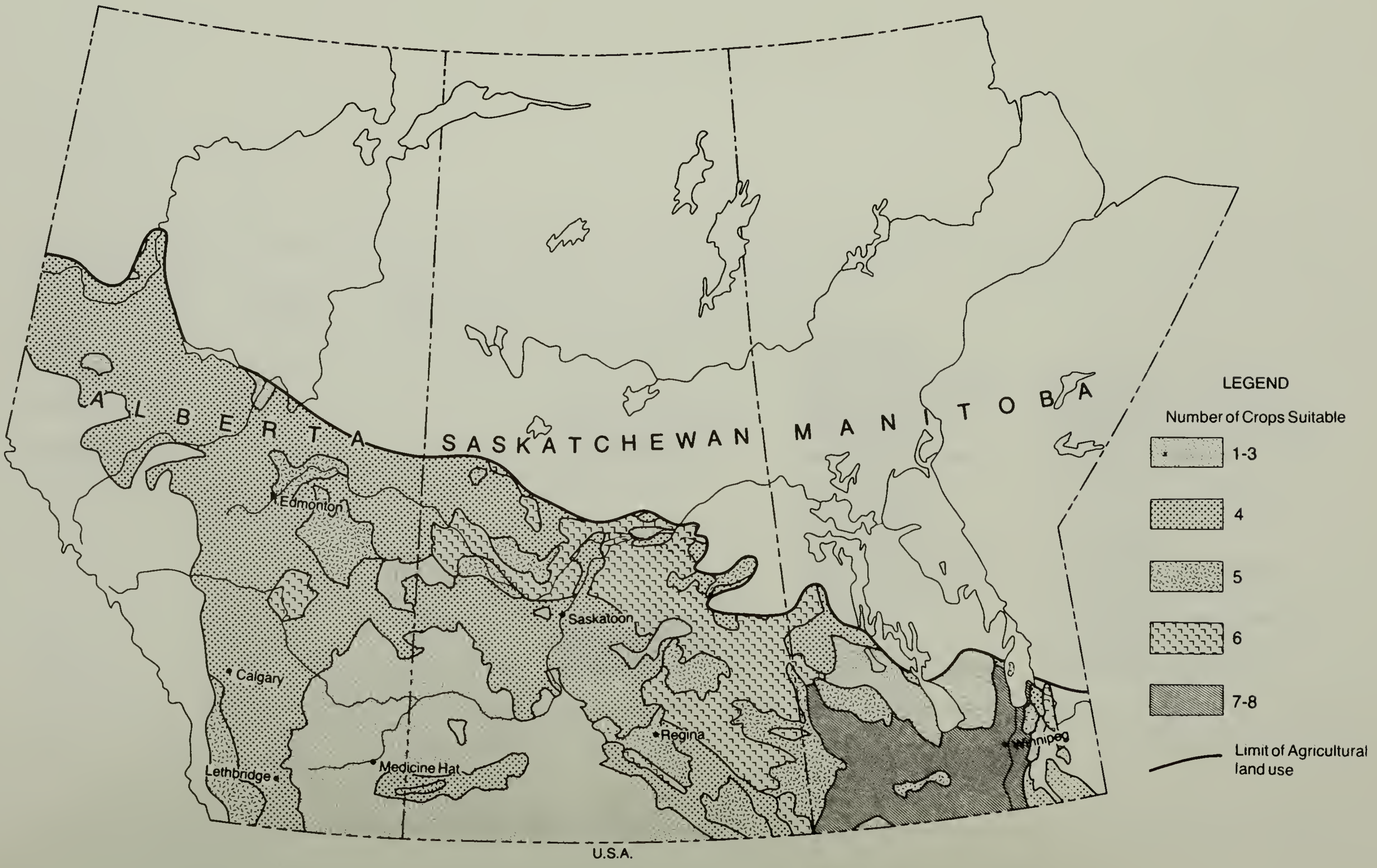

Figure 5.1 Land use flexibility according to soil and climate suitability.

flexibility. Equally important are factors such as potential yield of the crop, market price for each, portion of the land area suitable and so forth. For example, a given area with capability for a high potential yield for a variety of crops, is inherently more reliable in production (and flexibility) than one with a much lower yield potential, with the same crop diversity. Similarily, regions with relatively uniform, high quality soils may be easier to manage and may be more flexible in use than those with diverse soil characteristics, assuming relatively similar farming systems and weather.

Theoretically, an index of land flexibility can be calculated as the product of some measure of crop yield times the probability of achieving that yield. Summed over the number of crops suitable in a given area, the equation becomes:

$$LF = \sum_{i=1}^{n} P_i \; Y_i \qquad (1)$$

where LF = land flexibility index
P_i = level of crop yield probability, crop i
Y_i = expected yield, crop i
n = number of crops being considered

Expressed in this manner, land flexibility varies according to the number of crops suitable in an area, the expected yields of the crops and the probability of achieving those yields. The highest possible index value would be equal to the number of crops in the equation. Economic (E_i) and other variables could be added if suitable data are available. All input values should be ratio estimates, thereby rendering the LF index dimensionless.

The type of LF rating obtained is directly dependent on the types of yield data used. For example if "actual" yield data are used for the yield variable (Y_i) then "actual" land flexibility would be calculated. However, such an index would only show how flexible an area was in the past, and it would be limited to crops which historically have been grown in that region; it would not provide information on crops with some economic potential for the area, but which are not currently being cultivated. A more useful alternative, therefore, would be to use potential yield estimates, giving a "potential" land flexibility index.

In the current study, LF values were calculated for up to 8 crops for the agricultural region of the prairie provinces. Input data were obtained from the Land Potential Data Base (LPDB). The LPDB contains estimates of anticipated crop yields calculated from a crop growth model (Stewart, 1983), estimates of soil and climate suitability (well suited, suited and not suited) and many other physical and climatological factors related to biological crop production. These values are available for each of the map unit areas of the LPDB, but costs of production and other economic variables are not available. For this reason only physical land factors could be included, thereby yielding a Physical Land Flexibility index (PLF).

Anticipated fresh weight yield values from the LPDB were used as estimates of rainfed potential yield (Yi) for all crops included in the study. Although calculated by a crop growth model, these values have been carefully verified against available data, and they have been shown to be within ±20% of measured potential yield values, (Dumanski and Stewart, 1983). Although this results in some variation for individual site values, other studies have shown these estimates to be among the most reliable estimates of potential yield currently available in Canada (LEG, 1984; C. Onofrei, personal communication). Potential yield values for each map unit were expressed as a ratio compared to the highest potential yield for that crop in the prairie area.

Soil and climate suitability ratings from the LPDB were used as surrogates for the probability factor (Pi) in equation (1). Although these two variables have different meaning they are related in the biological sense. It is logical that an area with well suited soil would have a higher probability of achieving the potential yield than one with lower suitability. Thus, although it is realized that the relationship is tenuous, suitability was assumed to be equivalent to yield probability for purposes of calculating PLF values. On this basis equation (1) became:

$$\mathrm{PLF} = \sum_{i=1}^{n} S_i \, Y_i / Y_{mi} \qquad (2)$$

where PLF = physical land flexibility index
S_i = portion of map unit area variously suited for crop i (%)
Y_i = anticipated fresh weight potential yield. (kg ha^{-1})
Y_{mi} = maximum anticipated fresh weight (potential) yield for crop i in study area (kg ha^{-1})
n = number of crops used in the analyses

However the LPDB contains three levels of suitability, S_{i1}, S_{i2}, S_{i3} for each map unit and for any crop i. S_{i1} is the portion of the map unit well suited for crop i, S_{i2} is the portion suited, and S_{i3} is the portion not suited. Since it can be assumed that the yield probability on land rated not suitable approaches zero, this term was deleted from the calculations and equation (2) became:

$$\mathrm{PLF} = \sum_{i=1}^{n} (S_{i1} + S_{i2}) \, Y_i / Y_{mi} \qquad (3)$$

Yield values, however, are not identical for well suited and suited areas. In the LPDB a yield deflater of 25% was applied to yields in suited areas compared to that in well suited areas (Dumanski and Stewart, 1983). On this basis equation (3) was changed to:

$$PLF = \sum_{i=1}^{n} (S_{i1} + 0.75\ S_{i2})\ Y_i/Y_{mi} \qquad (4)$$

Values of suitability and potential (anticipated fresh weight) yield by crop for each polygon in the prairie region were obtained from the LPDB. Data records were validated and updated where necessary and sorted by province, Great Soil Group and polygon to facilitate data analysis. The major updates involved ensuring that all suitability ratings were consistent, and that crop yields were revised according to updated suitability estimates. PLF values for each polygon in the prairie region were then calculated according to equation (4).

Mean PLF values for the Chernozemic soils in the prairie region are shown in Table 5.2 and Figure 5.2, grouped by soil Great Group and particle size class. Values were also calculated for the Solonetzic and Gray Luvisolic soils, but the sample size was insufficient to give reliable estimates in these cases. Results show that the highest flexibility occurs in the Black Chernozemic soils, followed by the Dark Gray Chernozemic, Dark Brown Chernozemic and Brown Chernozemic soils in that order. This reflects the interaction between soil moisture and growing season temperature, in progressing from the warmest and driest areas in the south to the cooler and more moist areas in the north and west. As a general group the Black Chernozemic soils are four times more flexible than the Brown, two times more flexible than the Dark Brown and 20% more flexible than the Dark Gray soils.

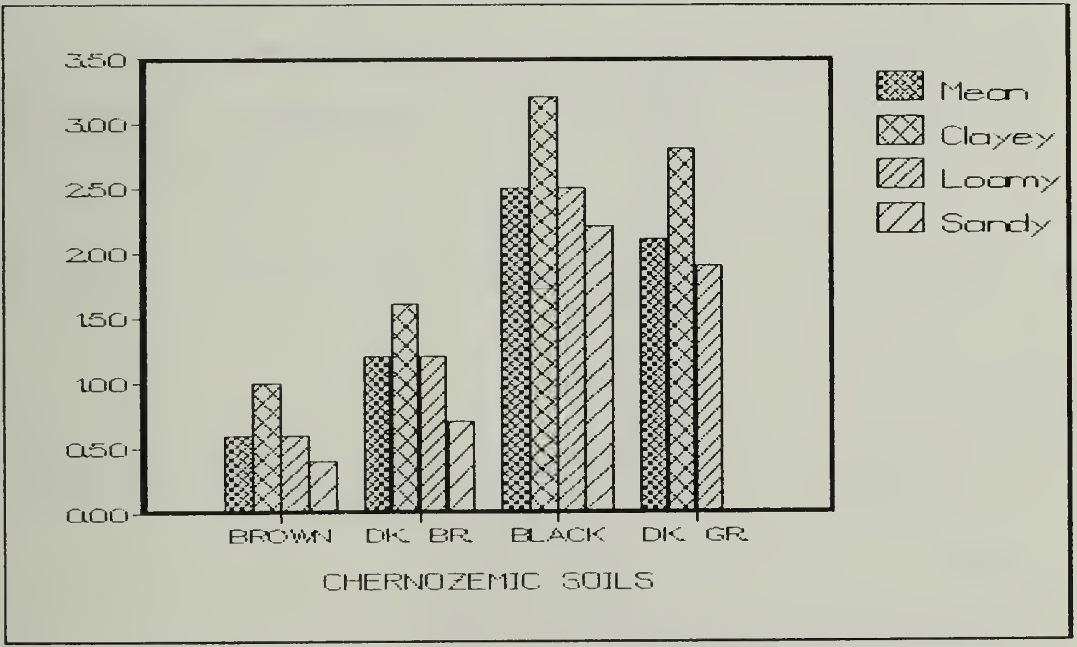

Figure 5.2 Physical land flexibility (PLF) values for Chernozemic soils for the prairie region.

PLF increases directly with increase in clay within each soil Great Group. This influence, however, is overriden by the climate effect, with the result that sandy soils in the Black Chernozemic area, for example, have considerably higher PLF values than even clayey soils in the Dark Brown and Brown zones, and loamy soils in the Dark Gray areas. The highest PLF values are found in clayey soils in the Black Chernozemic zone, and the lowest on sandy soils in the Brown Chernozemic zone.

The PLF index has its highest interpretive value when used to compare one area against another. Used in this manner, these values provide a comparison of flexibility potential relative to a standard. In this study the Red River Plain (map unit G1/14), which had the highest PLF value in the region (5.03) was selected as the standard, and all others were compared to this.

Table 5.2 and Figure 5.3 show the results when each map unit in the prairie region is compared to the Red River Plain. In general, southern Manitoba has the highest degree of flexibility, averaging in excess of 80% of that of the Red River Plain. This is followed by several areas in east central Saskatchewan and eastern Manitoba which are 60-80% of the Red River Plain. The remainder of eastern and northern Saskatchewan, western Manitoba, and western and northern Alberta including most of the Peace River area, are 40-60% of the standard. The largest portion of the prairie area, however, encompassing most of the cultivated land in the southern and central portions of the area and in the north, has PLF values less than 40% and often less than 20% of those of the Red River Plain. Land use diversity and alternate cropping options are highly restricted in these latter areas. Conversely these areas generally have the most reliable weather for harvest, and the highest quality grain.

Table 5.2. Physical Land Flexibility (PLF) values for 8 crops in the Prairie Region

	Brown Chem.				Dark Brown Chem.				Black Chem.				Dark Gray Chem.*		
	Mn	S	L	C	Mn	S	L	C	Mn	S	L	C	Mn	L	C
PLF index (8 crops)	0.6	0.4	0.6	1.0	1.2	0.7	1.2	1.6	2.5	2.2	2.5	3.2	2.1	1.9	2.8
PLF compared to maximum PLF (map unit G1/14)%	12.4	6.6	12.3	20.1	24.0	15.1	24.2	31.7	50.4	43.9	48.5	67.0	41.9	36.9	55.4
Number of polygons (sample size)	24	6	14	4	31	4	23	4	42	3	34	5	15	11	4

* Sample size for sandy Dark Gray Chernozemic soils was too small to be reliable.
** Mn,- Group Mean; S, Sandy; L-Loamy; C-Clayey.

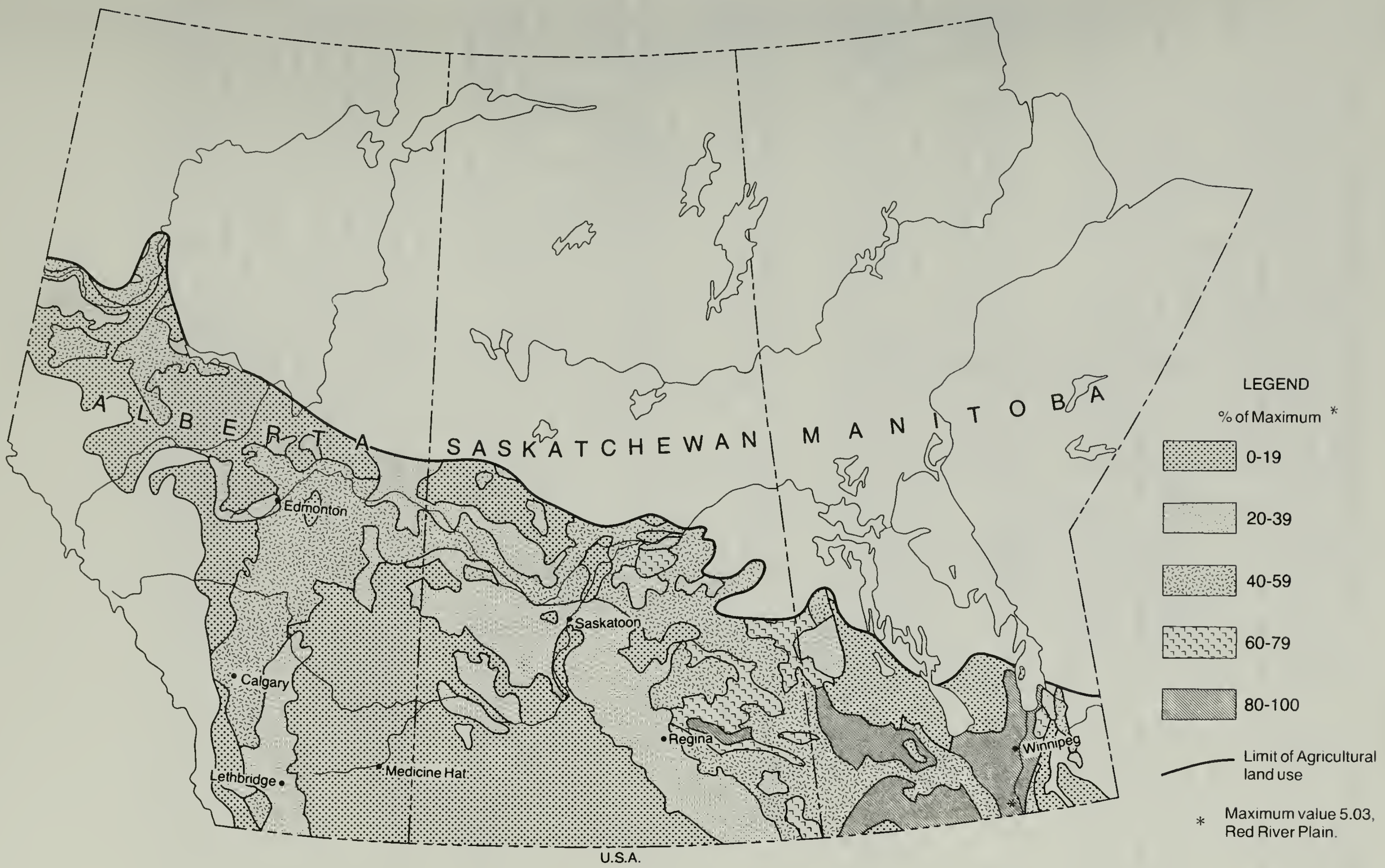

Figure 5.3 Physical land flexibility (PLF) for eight crops compared to regional maximum.

Generally, the stratification of comparative flexibility closely follows the regional soil Great Group boundaries (Table 5.2, Fig. 5.3), but with considerable variation within each group due to soil texture. The Brown Chernozemic soils are only about 6.6 to 20.1% as flexible in their use compared to the Red River Plain, with a group mean of about 12.4%. The Dark Brown soils, except for the Regina, Weyburn and Lethbridge areas which are higher, range from 15.1 to 31.7% and average about 23.9%. The Black Chernozemic soils have the highest values ranging from 43.9% on sands to 67.0% on clays, with a group mean of 50.4%. The Melfort, Kamsack, Balcarres, Estevan and Beausejour areas however, have higher values. The Dark Gray Chernozemics have values of 36.9% on loams to 55.4% on clays, with a group mean of 41.9%. Interestingly, the flexibility in the Gray Luvisols is generally similar to that in the Brown Chernozemics.

As noted previously, the Black Chernozemic soils have notably the highest values in comparative flexibility. This underlines the considerable natural advantage in these soils to buffer against outside stress factors such as drought. It also points out the strategic importance of these soils in terms of long term production possibilities in the prairie region. These soils have the highest production capacity and they are highly responsive to management. In decreasing order of dependability, the Black Chernozemic soils are followed by the Dark Gray Chernozemics, the Dark Brown Chernozemics, and the Brown Chernozemics and Gray Luvisols.

PLF values, as used in this study, are interpretations of map unit area, rather than individual soils, and thus are scale dependent. For example, a map unit with a high proportion of well suited soils will receive a higher rating than one with a lower proportion of similar soils. Also, all crops are treated uniformly, and as a consequence, the index will be biased upward by the highest yielding crops, regardless of whether or not these crops are economically attractive. Similarily, because PLF is a ratio estimate summed over several crops, values may be distorted by the relationship between average yield and the highest regional yield for individual crops. For example, if average yields for a crop are reasonably close to the standard used as the highest regional yield, then PLF values will be distorted upward for that crop. Conversely, if average values for a crop are low compared to the highest regional yield, then these crops will have minimal influence on the PLF index.

Some of these concerns were reduced by the types of data used in the analyses. The study was conducted at a scale of 1:5 M, using polygons from the Soils of Canada map. At that scale this is the best information base available. The question of average to highest regional yield was circumvented by using potential rather than actual yield values. In this way the differences should be relatively realistic estimates of comparative production possibilities. The differences in yield potential between crops, however, was not handled in this study, nor were differences in ease of harvest, crop quality or potential land use changes due to improved moisture management or summerfallow reduction. These remain as areas for further research.

Physical Land Flexibility (cereals) Related to Actual Land Use and Performance

Studies of potential land flexibility are useful to identify the production advantages or disadvantages of certain areas compared to others. Equally useful, however, is information on how current land use and production compares with these estimated potentials.

Theoretically this can be achieved by comparing the amount of land currently in production to the amount of land estimated to be suitable in each map unit area, and by comparing actual crop yields in the map unit with potential yields for each crop considered. This would give a flexibility ratio based on actual PLF compared to potential PLF. By summing up the results for all crops that are or could be grown in an area, a ratio describing the amount of potential flexibility that is currently being utilized could be calculated. These calculations however, are done using actual and potential values for each map unit area, rather than by using a regional standard as reported earlier.

Such an approach, although conceptually appealing, was found to be operationally impossible at the current time because of an inadequate data base on current crop yields. The LPDB relies on Crop Reporting District data for actual yield values, and although these data are complete for cereals (wheat, oats, barley), they are inadequate for most other crops used in this study. Another problem was that no suitable partitioning algorithm could be found to allocate land to several crops at the same time, considering that land suitable for one crop is, in many cases, also suitable for several others.

For these reasons, only an approximation of such a flexibility ratio was calculated, based on the cereal crops, wheat, oats and barley. This was achieved by the following equation:

$$PLF_r = \sum_{i=1}^{n} \frac{A.\ Yai}{(Si_1+0.75Si_2)Y_i} \qquad (5)$$

where PLF_r = physical land flexibility ratio; portion of land flexibility currently being utilized
A = portion of map unit cleared for agriculture (1981 census), including cropland, summerfallow, hay and improved pasture (%)
Y_{ai} = average reported yield values (1979-83) for crop i (kg ha^{-1})
S_{i1} = portion of map unit well suited for crop i (%)
S_{i2} = portion of map unit suited for crop i (%)
Y_i = anticipated fresh weight (potential) yield for crop i (kg ha^{-1})

Values for suitability, potential yield and the 5-year average of actual (reported) yield were obtained from the LPDB for each map unit in the prairie region. Data for the amount of land cleared for agriculture were obtained from the Census, and converted to a map unit basis by using a standard weighting procedure. The data were standardized and verified before analysis, primarily to ensure that the suitability for wheat was less than or equal to that for oats and barley, and that potential yields were greater or equal to actual yields (in the few instances where actual yields exceeded the calculated potential yields, potential yield was set equal to actual yield).

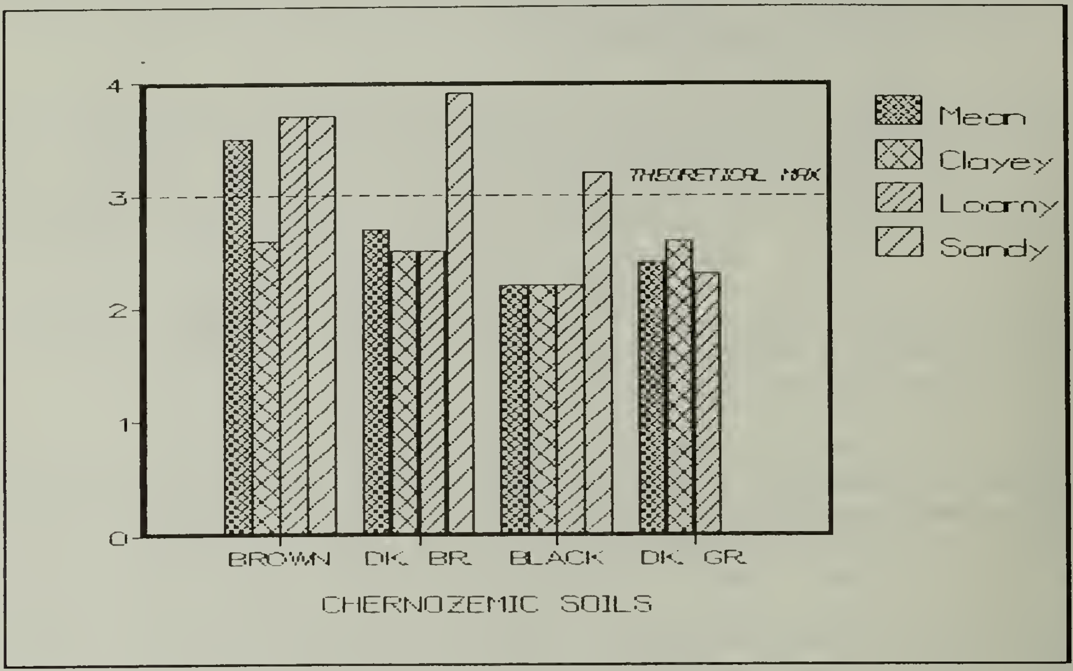

Figure 5.4 Physical land flexibility ratios (PLF_r) for Chernozemic soils in the prairie region.

Values for PLF_r were calculated for each map unit in the prairie region according to equation (5). The data (Table 5.3, Fig. 5.4, Fig. 5.5) show that the theoretical upper limit for physical land flexibility for cereals is exceeded in sandy soils in all cases, and in loamy soils in the Brown Chernozemic soil area (Fig. 5.4). This could be because potential yields in these areas are underestimated, and/or because the amount of land under cultivation is greater than that estimated to be suitable. Whatever the reason, this indicates that these soils are likely being used beyond their capability, and thus are more subject to degradation (other conditions being equal). Production pressures on these soils should be reduced if they are to be maintained in a sustainable manner. In the drier areas this might involve land retirement to permanent forages, whereas in other regions increased use of forage rotations as well as land retirement would be appropriate. Conversion to summerfallow, however, should be avoided.

In general the potential land flexibility of the Black Chernozemic soils is the most under-utilized in the region (Table 5.3, Fig. 5.4), followed by the Dark Gray Chernozemic and Dark Brown Chernozemic soils. The Brown Chernozemic soils, on the other hand, might be over-utilized. This again demonstrates the superior comparative advantage of the Black Chernozemic soils relative to the others. It may also reflect the predominance of the wheat-fallow production system in this area.

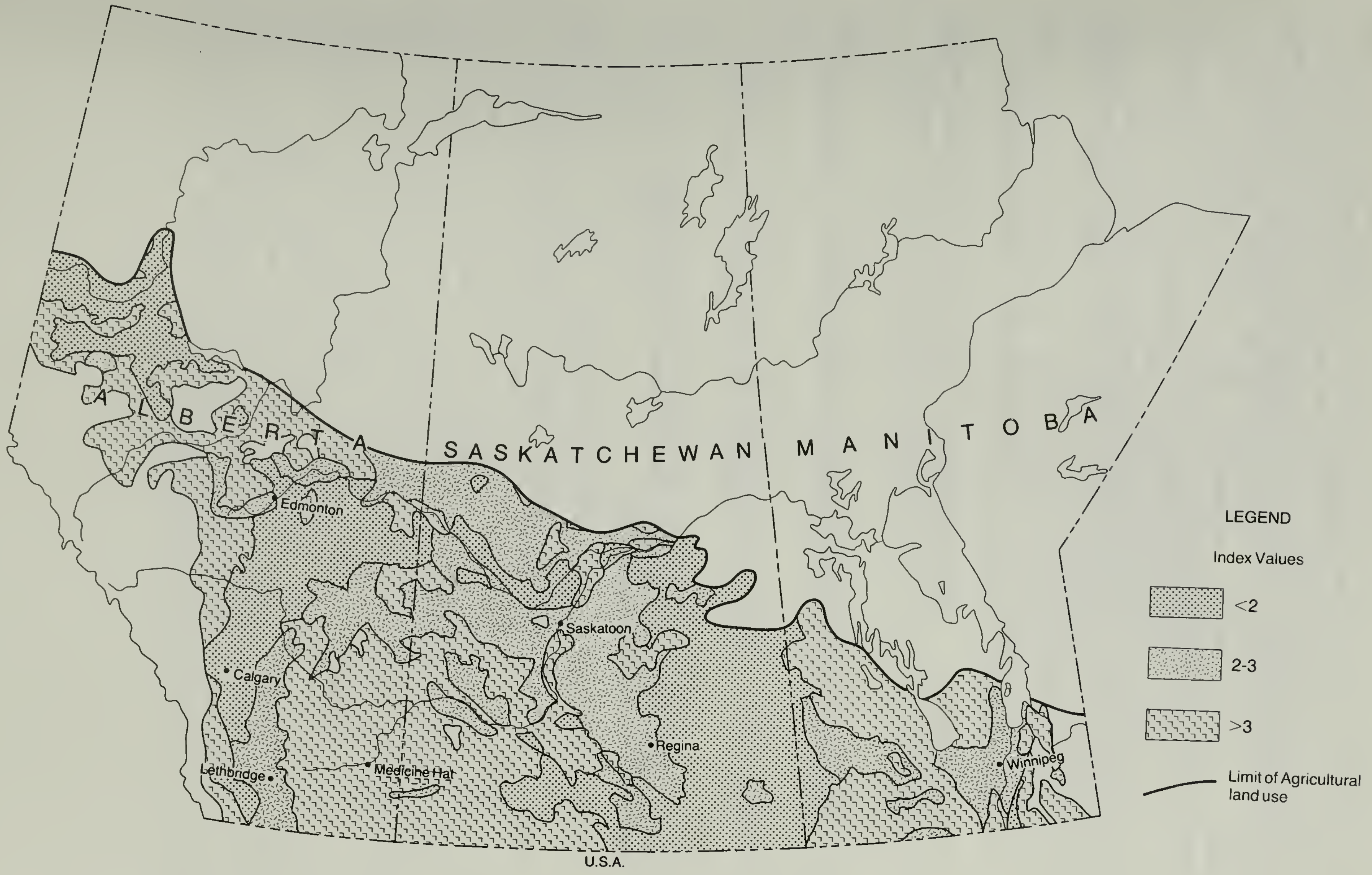

Figure 5.5 Geographic distribution of physical land flexibility ratios (PLF_r) in the prairie region.

The geographic distribution of PLF$_r$ values in the prairie region is shown in Fig. 5.5. This demonstrates that three major areas are significantly under-utilized in relation to their potential, namely eastern Saskatchewan, western Alberta and the Peace River area. Expanded production activities can be envisaged in these areas. Conversely major areas in southwestern Saskatchewan, eastern Alberta, southwestern and eastern Manitoba and the northern agricultural fringe might be over-utilized. These are areas where reduction in cultivated areas would appear to be warranted. The balance of the area is just under the theoretical upper limit of land use flexibility, but certain regions, particularily in Manitoba and central Saskatchewan, are very close to this limit. Increased use of rotations, better land management and land retirement in some cases may be necessary in these regions in the future to reduce production stress.

Table 5.3. Physical Land Flexibility Ratios (PLF$_r$) for Cereal Crops in the Prairie Region

	Brown Chem.				Dark Brown Chem.				Black Chem.				Dark Gray Chem.*		
	Mn	S	L	C	Mn	S	L	C	Mn	S	L	C	Mn	L	C
PLF$_r$ value (cereals)	3.5	3.7	3.7	2.6	2.7	3.9	2.5	2.5	2.2	3.2	2.2	2.2	2.4	2.3	2.6
Number of polygons (sample size)	20	2	14	4	30	4	22	4	39	3	32	4	14	10	4

* Sample size for sandy Dark Gray Chernozemic soils was too small to be reliable
** Mn.- Group Mean; S.- Sandy; L-Loamy; C-Clayey.

Physical land flexibility ratios (PLF$_r$) are comparisons of the amount of land in agricultural use to the amount of land potentially suitable, and of the mean actual yields of individual crops to the potential yields for these crops. Although the ratio can usefully identify areas with residual potential for expansion as well as regions where production stresses may be giving cause for concern, the results must always be interpreted in relation to the assumptions used in developing the index. Firstly, these values incorporate all of the weaknesses of the PLF index, namely scale dependency, crop dependency and yield ratio dependency. Secondly, the amount of land cleared for agriculture, the A value, is used as a surrogate for the area of land used for an individual crop. This is acceptable in studies involving highly comparable and edaphically interchangeable crops such as those in the cereals group, but it would be highly tenuous for more complex crop mixtures. Further development on this aspect is required. Also the effect of summerfallow on land flexibility ratios, and the relation of this to degradation should be evaluated.

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APPENDIX

PRODUCTION REQUIREMENTS FOR WINTER CEREALS ON THE PRAIRIES

G. PADBURY

INTRODUCTION

This report deals specifically with the crop requirements and management strategies related to the production of winter cereals on the Canadian prairies. The information was obtained mainly from publications of the Crop Development Centre at the University of Saskatchewan and is intended to provide part of the information necessary for the development and application of a land suitability classification scheme for these crops.

CROP REQUIREMENTS

The crop requirements associated with the production of winter cereals are similar in most respects to those of spring-sown cereals with one major exception: winter survival. And it is winter survival that, in essence, governs the relative success of fall-seeded cereal crops on the Canadian prairies.

Winter Survival

Without previous exposure to near-freezing temperatures, winter cereals, when subjected to subfreezing temperatures, will survive no better than spring cereals. When exposed to cool fall temperatures, however, winter cereals undergo two important physiological changes: vernalization and acclimation. Vernalization is required before heading will occur the following summer; cold acclimation is necessary for the plants to survive the low temperatures of winter. As shown in Fig. 1, the minimal survival temperature for winter wheat decreases dramatically from about - 3°C at the beginning of September, to - 19°C or lower by the end of October. An even more dramatic decrease in survival occurs for winter rye (Fig. 2).

About 6 to 8 weeks are required for the full development of winter hardiness. The first 4 to 5 weeks is a period of active growth, which is necessary to provide a healthy, vigorous plant with a well-developed crown. During the second stage, which is initiated when morning and afternoon temperatures drop below 7 and 10°C respectively, the rate of plant growth slows appreciably and the rate of cold acclimation increases. At the end of this second stage, which is usually about 3 to 4 weeks, a period of continuous frost is required to fully harden the plants. Although exposure to warm temperatures during this period will result in rapid dehardening, once the plants are returned to near freezing temperatures they will quickly reharden.

Once cold acclimation has taken place, a high level of hardiness can be maintained provided temperatures remain below freezing. Reduced cold hardiness will likely result if temperatures slightly above freezing or slightly about the killing temperature are maintained for prolonged periods. Alternate freezing and thawing will also reduce cold hardiness.

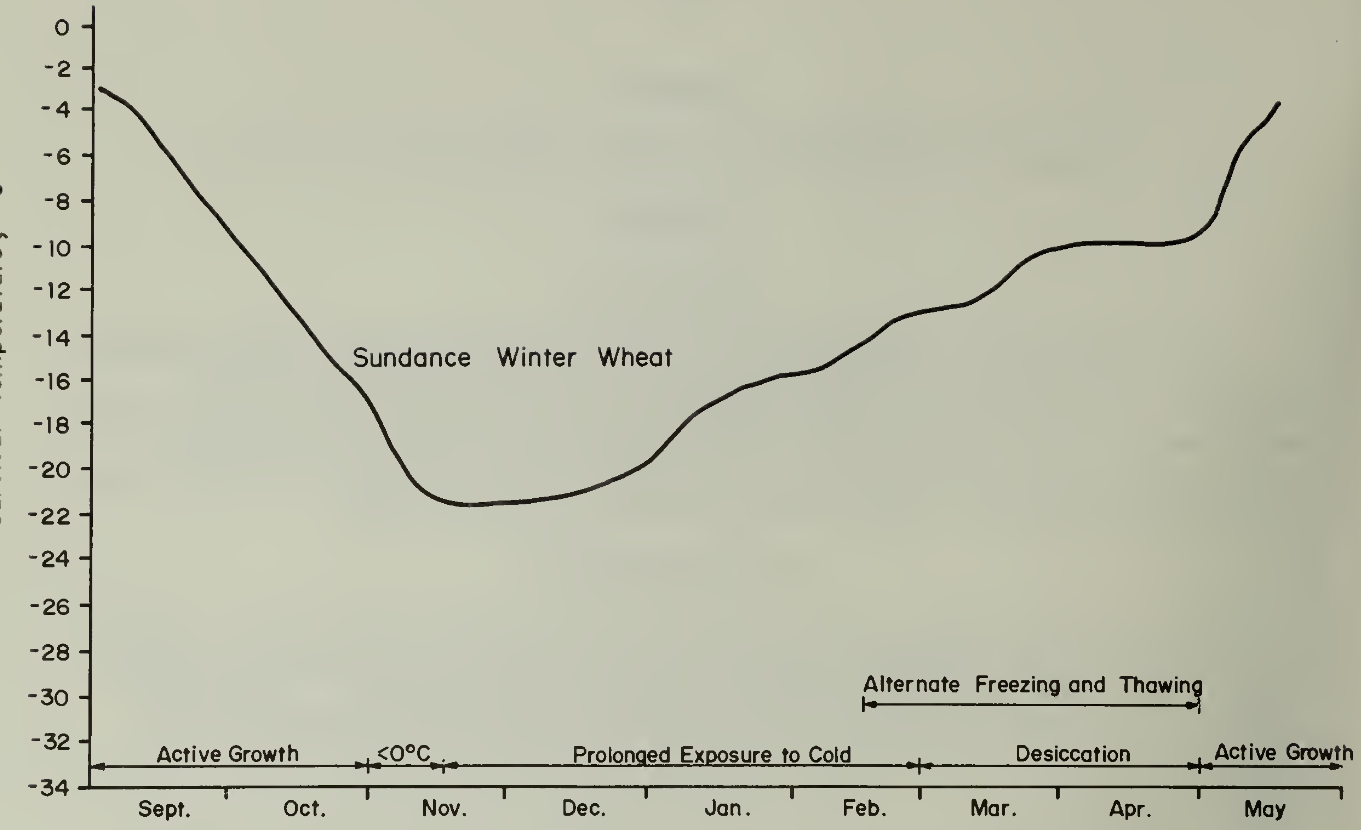

Figure 1. Changes in cold hardiness of Sundance winter wheat for the period September to May.

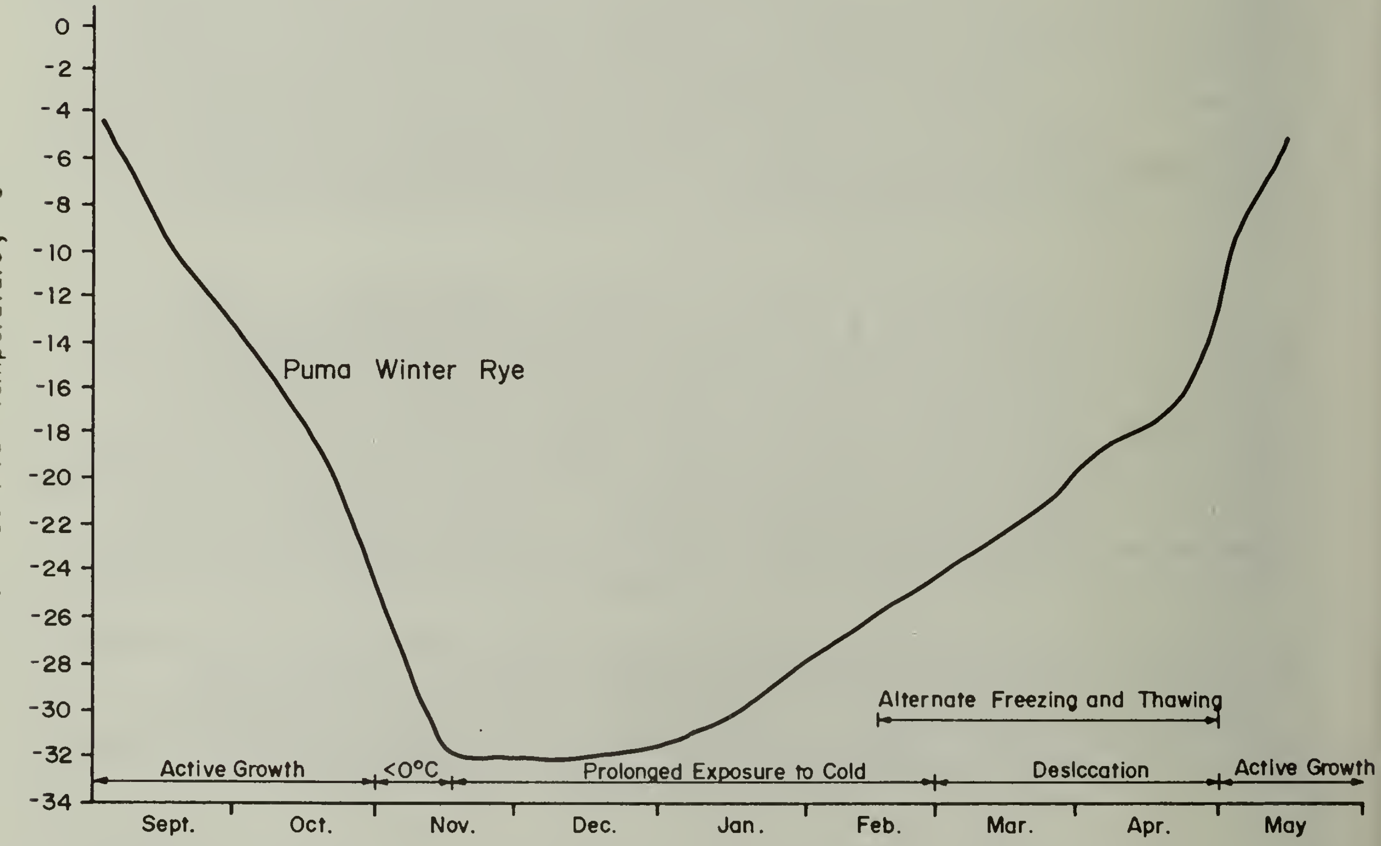

Figure 2. Changes in cold hardiness of Puma winter rye for the period September to May.

Exposure to warm spring conditions will eventually result in a complete dehardening of the plant. Once the dehardening process has been initiated in the spring, it cannot be reversed and a loss of cold hardiness will result even if the plants are maintained at temperatures below freezing.

Cold Tolerance Potential of Cultivars

Winter cereals vary in their ability to withstand cold temperatures. To provide a measure of a cultivar's winter survival ability, comparative FIELD SURVIVAL INDICES (FSI) can be determined utilizing field survival data. The higher the cultivar's FSI, the greater its ability to survive cold temperatures. Cultivars representative of the cold hardiness range within each species are listed in Table 1, which demonstrates that although there is an overlap among species, cultivars of rye have the best cold hardiness potential, those of durum wheat, barley and oats have the least potential, and cultivars of wheat and triticale are intermediate. The FSI for winter wheat cultivars given in Table 2 were derived from field trials in Saskatchewan from 1972-77. This material is representative of cultivars grown in the winter wheat producing areas of the world and includes the hardiest strains that have been identified to date.

Table 1. Winter cereal field survival indices, derived from lab tests.

Cultivar or Strain	Species	FSI
Unacclimated		
	Spring or winter wheat	70
	Spring or winter rye	90
Acclimated		
Random	Spring oats	115
Bonanza	Spring barley	115
Manitou	Spring wheat	160
Gazelle	Spring rye	210
WIR 46870	Winter durum wheat	255
Penium	Winter oats	275
WIR 46870 + Cougar	Winter triticale (6X)	275
Compactum	Winter oats	290
Dover	Winter barley	300
Cappelle Desprez	Winter wheat	306
Dicktoo	Winter barley	355
Novamichurinka	Winter durum wheat	370
Kharkov + Puma	Winter triticale (8X)	460
Ulianovkia + Kodiak	Winter triticale (8X)	480
Kharkov	Winter wheat	501
Ulianovkia	Winter wheat	530
Sangaste	Winter rye	550
Kodiak	Winter rye	575
Cougar	Winter rye	620
Frontier	Winter rye	735
Puma	Winter rye	735

It should be recognized that recent improvements in winter wheat survival potential have been minimal and that, if anything, the cold hardiness potential of some recent cultivars is lower than that of some established ones. In fact, the total North American breeding effort expended since the introduction of the Crimean wheats in the late 1800's has produced only marginal improvements in cold hardiness. The main reason for this lack of progress has been the limited genetic variability for cold hardiness; a similar situation appears to exist for barley and oats. Although the cold hardiness of rye is evidence of the potenital of winter cereals to survive cold temperatures, it is estimated that with the material at hand and from what is known of the genetics of cold hardiness, even an intensive winter wheat plant breeding effort would result in little more than a 15% increase in FSI over that of Norstar.

Table 2. Winter wheat field survival indices, derived from field trials.

Year Commerically Available in North America	Cultivar or Strain	Area of Adaption or Initial Release	FSI
-	Cappelle Desprez	France	306
1969	Ionia	Michigan	345
1972	Arrow	New York	345
1967	Blueboy	North Carolina	358
1968	Yorkstar*	New York	360
1971	Fredrick*	Ontario	368
1965	Nugaines*	Washington	376
1973	Tecumseh	Michigan	386
1961	Gaines*	Washington	389
1975	Lancota	Nebraska	392
-	Besotoia 1	USSR	401
1946	Rideau*	Ontario	405
1971	Centurk	Nebraska	433
1970	Scoutland	Nebraska	444
1967	Scout 66	Nebraska	444
1922	Cheyenne	Nebraska	445
1960	Warrior	Nebraska	446
1961	Winalta*	Alberta	463
-	Mironovskaja 808	USSR	466
1968	Froid	Montana	488
1902	Minhardi	Minnesota	492
1932	Yogo*	Montana	493
1965	Hume	South Dakota	493
1971	Sundance*	Alberta	494
1912	Kharkov 22MC*	Quebec	499
1977	Norstar*	Alberta	514
-	Alabaskaja	USSR	527
-	Ulianovkia	USSR	530

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* Licensed for production in Canada

Management Considerations

Important cultural practices for winter cereal survival include seeding with a hoe press or zero tillage drill into a moist field of standing stubble or other snow traps on the recommended date with the recommended fertilizer levels. Shortfalls in any one of these practices result in a reduction in cultivar cold hardiness potential (FSI). The units used to measure this failure are the same as for the cultivar FSI's and, therefore, the consequences of management deficiencies can be determined for each cultivar. Comparison with minimum cultivar FSI's required for undamaged stands provides an estimate of survival.

Seeding Date

Seeding date has a major influence on the success of winter cereal production. Because winter wheat survives the winter in the seedling stage, healthy vigorous plants must be established before freeze-up to provide optimum energy reserves for the following spring. The main factor dictating seeding date is soil temperature, and for this reason the optimum seeding date ranges from about August 25 for the north, to September 10 for the extreme south of the agricultural area in Western Canada (Table 3).

Table 3. Optimum date of seeding winter wheat into standing stubble.

Location	Optimum Date
Lethbridge	September 9
Maple Creek; Estevan	September 6
Kindersley; Swift Current	September 3
North Battleford; Saskatoon; Yorkton	August 30
Meadow Lake; Prince Albert; Nipawin	August 27

Seeding too early can result in excessive growth in the fall and plants which are increasingly susceptible to winter injury and diseases such as root rot. This, however, is not usually a problem with stubbled-in winter wheat as removal of the previous crop rarely occurs before the optimum seeding date. Late seeding can also result in plants that are less cold tolerant than those seeded on the optimum date (Fig. 3). Yield reductions (Fig. 4), delayed heading, delayed maturity (Fig. 5), reduced bushel weights, and increased weed problems are also often associated with late seeding.

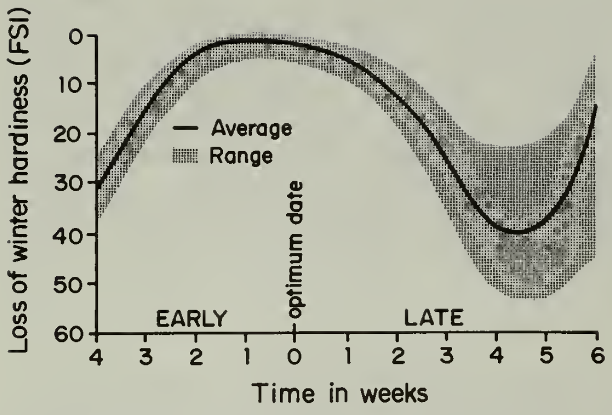

Figure 3. Influence of seeding date on the winter hardiness of winter wheat.

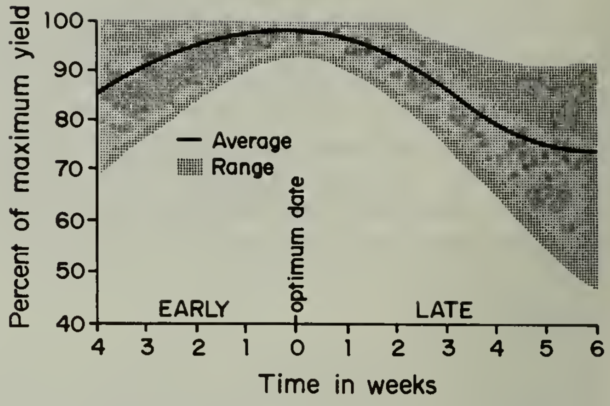

Figure 4. Influence of seeding date on the yield of winter wheat.

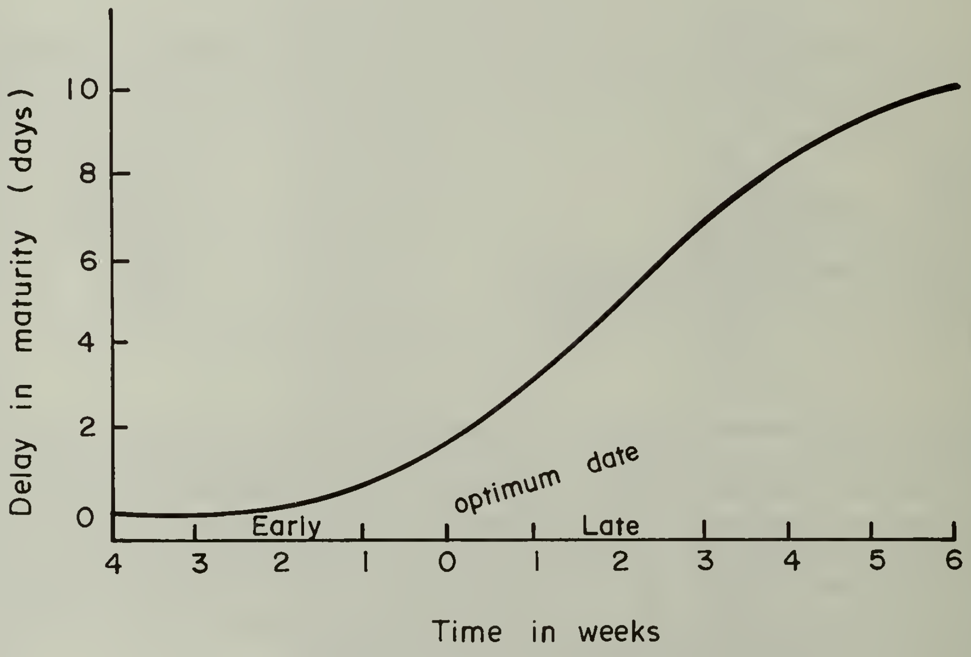

Figure 5. Influence of seeding date on the maturity of winter wheat.

It is obvious that variables such as soil moisture, soil temperature and seeding depth all interact making it difficult to predict seedling establishment, not to mention the uncertainty of subsequent weather conditions which may, on occasion, favor suboptimal seeding dates. Thus, responses to seeding date cannot always be predicted by adhering to the calendar. In general, seeding when the afternoon soil temperature is approximately 18°C usually allows sufficient time for this growth and development to take place before freeze-up (Tables 4 and 5).

Table 4. Average soil temperature in stubble fields for the 6-week period starting at optimum seeding date.

Weeks after Optimum Date	0	1	2	3	4	5	6
	Soil temperature (°C)						
9 a.m.	13	12	10	9	8	6	5
4 p.m.	18	16	14	13	11	9	8

Table 5. Influence of soil temperature on emergence of winter wheat seeded into moist soil.

Soil Temperature (°C)	Days to Emergence
25	4
20	6
15	8
10	12
5	30

Seedbed Preparation

Hot, dry weather, which often occurs in late summer, quickly dries out loose, open soils, resulting in uneven germination and weak seedings which are extremely prone to winter killing. The estimated reduction in FSI for plants entering the soil in this condition is 150%, which is sufficient to almost guarantee a crop failure for the hardiest of winter wheat cultures. On summerfallow, shallow tillage in late season operations is the best means of maintaining a firm seedbed. No seedbed preparation is needed for stubble seeding, although good drill penetration is required.

The optimum seeding depth on both summerfallow and stubble is less than 4 cm into firm, moist soil. Deeper seeding often results in delayed emergence and weak plants which are susceptible to winter killing. Stubble fields from which crops have just been harvested are often low in soil moisture, although that required for germination of wheat is quite low, sometimes lower than the permanent wilting point.

Fertilizer Application

Positive yield responses have been obtained from fertilizer application on winter cereals, particularly for stubble land. In general, field trials have shown that nitrogen deficiences, for the most part, do not have a negative effect the cultivar's cold hardiness potential, while phosphorus deficiencies do. As a result phosphate is generally applied in the fall with the seed, while nitrogen deficiencies are generally corrected by broadcasting ammonium nitrate at the recommended rate in the spring after the survival level has been assessed, although some N may be applied with the seed. (Table 6).

Table 6. Effect of phosphate fertilizers on winter survival.

	Subtract (Cultivar FSI)
Minimum requirements met	0
15 kg/ha deficiency P	25
30 kg/ha deficiency P	35

Snow Trapping

For winter cereals to survive the winter, the crown tissue must remain viable. The crown tissue is the area at the base of the plant from which secondary roots develop and is usually found at a depth of about 5 cm. Death of the crown tissue will result if the temperature falls below its minimum survival temperature at any time during the winter.

Although the soil has a significant capacity to buffer soil temperature change, the extremely low temperatures that occur during the prairie winter make it almost a necessity that some form of insulation be present to prevent soil temperatures from falling below the minimum required for surivival of most winter cereals. This insulation comes in the form of snow. Based on recent field trials, a cultivar FSI of greater than 650 is required to ensure an undamaged stand on bare summerfallow. This means that only the hardiest winter ryes grown under optimum management would have a change of surviving a prairie winter under such conditions.

As little as 5 cm of snow greatly reduces the cold hardiness requirement, although the risk for winter wheat is still high (Table 7). With 10 to 15 cm or more of snow cover, cultivars with a survival index greater than 430 are good risks. This includes Winalta, Yogo, Sundance, Kharkov and Norstar winter wheats (Table 2), but it essentially precludes presently available cultivars of winter oats, barley and durum wheat because of their lack of cold hardiness.

Several techniques of snow trapping have been considered: 1) thin stands of canola, flax or other summer annual grown as a companion crop with winter wheat; 2) trap strips of summer annual crops or perennial grasses sown at intervals across the wheat field perpendicular to the prevaling wind; 3) tree shelterbelts; and 4) direct seeding into standing stubble or 'zero-till' cropping.

Although all have the potential to trap snow, it is the latter that has proven most successful. To maintain standing stubble for a snow trap, one of two approaches can be used: 'zero-till' summerfallow, and seeding directly after harvest of the stubble crop.

Table 7. Minimum cultivar field survival indices required for undamaged stands.

	FSI
Bare summerfallow	650 or greater
5 cm snow cover	540
10 cm snow cover	430
> 15 cm snow cover	420 or less- snow mold hazard

Diseases

Several species of snow molds have been isolated from winter wheat and rye fields on the prairies and have, on occasion, caused serious damage. Prolonged, deep snow cover tends to favor snow mold. Moreover, populations of these organisms tend to increase with frequent winter cereal cropping of the same fields.

Flooding

Spring flooding following snowmelt can severely damage winter cereals and, for this reason, poorly drained areas or those subject to frequent or even periodic flooding are unsuitable for winter wheat production.

Early spring flooding with cold water usually does not cause damage. But once the water warms, deterioration of the crop is often rapid. Plants will survive longer if they are not completely submerged.

As a general rule, flood damage is less severe on stubbled-in compared to summerfallow-seeded winter cereals, the logic being that stubble fields are generally drier than summerfallow ones and are thus less subject to runoff and are able to absorb more water once the frost comes out of the soil in spring. Also of consideration is the fact that where spring flooding is serious enough to damage stubbled-in winter wheat, it would also preclude the seeding of spring cereals as well.

Growth and Yield

Soil Fertility

Although maintenance of snow cover is the major factor in successful winter wheat production on the Canadian Prairies, other factors must also be considered. Among the most important is the provision of adequate nutrients to the crop, which, in most areas, means the addition of fertilizers containing nitrogen and phosphorus and, in a few instances, sulfur and potash as well.

Because of the large nutrient drain made by the previous crop, most stubble fields have insufficient available N to provide for the needs of a winter wheat crop. Moreover, since most of the N demand of the winter wheat crop occurs before the end of June, N released through stubble decay will, in all likelihood, not contribute significantly (Fig. 6). As a result, the addition of N fertilizer usually has a dramatic effect on winter wheat yields, in fact, the response is often much greater than that for spring wheat (Fig. 7).

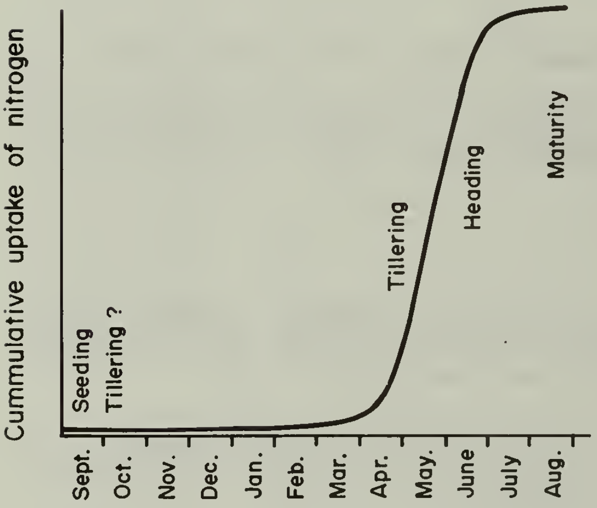

Fig. 6. Nitrogen uptake by winter wheat.

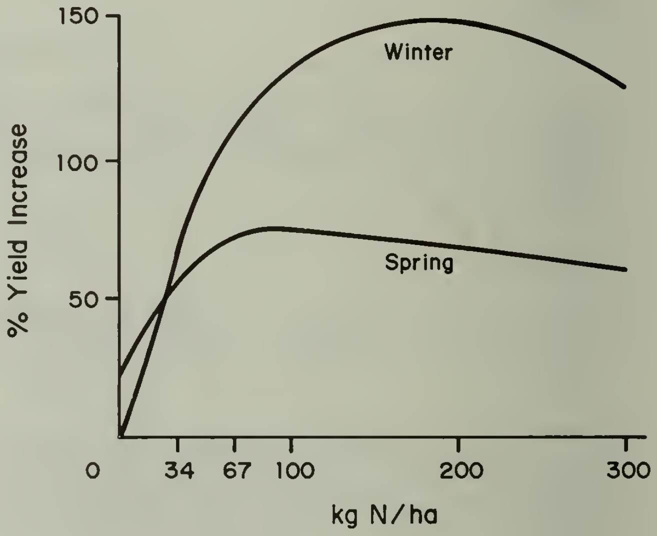

Fig. 7. Effect of nitrogen fertilizer on yield of spring and winter wheat, where mositure is sufficient.

Piebald or starchy kernel samples are often associated with stubbled-in winter wheat grown on nitrogen-deficient soils. If the occurrence of piebald kernels is high, the grade will be reduced.

Phosphorus deficiencies are also common with winter cereal production on the Prairies. Correcting phosphorus deficiencies using fertilizers not only increases yield, but also improves the winter wheat plants' ability to recover from winter damage and advances its maturity. For maximum response to phosphorus, deficiences in N also need to be corrected (Fig. 8).

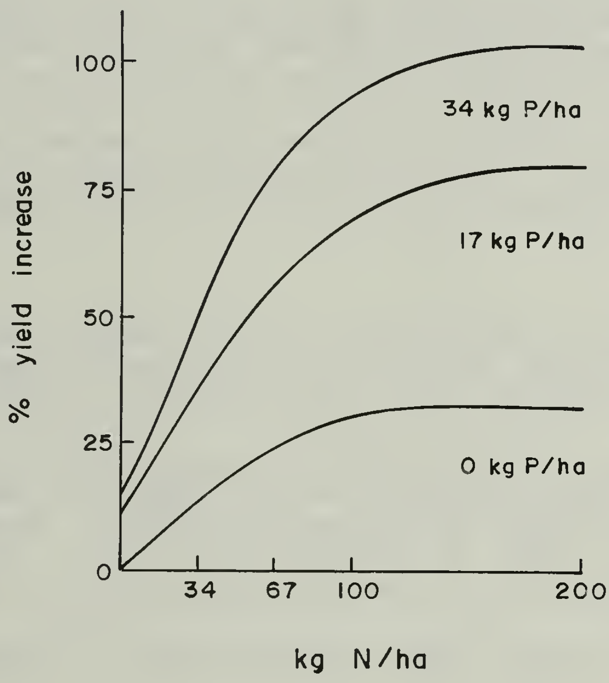

Figure 8. Effect of nitrogen and phosphorus fertilizer on yield of winter wheat, where mositure is sufficient.

The nutrient requirements of winter wheat are similar to those of spring wheat for all nutrients except nitrogen which are about 10 to 15% higher for winter wheat than for spring wheat. The nutrient requirements of fall rye are essentially the same as those for spring rye or spring wheat.

Soil Moisture

Soil moisture requirements for successful winter cereal production are twofold: first, sufficient soil moisture is required at or near the optimum seeding date in the fall to promote germination and the subsequent development of healthy, vigorous plants which are capable of surviving the winter; and second, soil moisture is required for growth and yield during the summer period similar to that for spring-sown cereals.

Moisture availability during the growing season is the one factor that most limits productivity on the prairies, especially in the Brown and Dark Brown soil zones. Cool, damp spring conditions are the most favorable environment for the growth of winter cereals, although there is the risk that if rainfall is limited and reserves run out by June or early July, yields may be poor. Early spring droughts and hot, dry winds at flowering time are also particularly damaging to winter cereals. Most severe droughts, however, occur in July and early August and by this time most of the growth of the winter cereals has occurred and the stress period is avoided.

Soil Salinity

Since crop damage due to soil salinity is usually aggravated by drought conditions which normally occur in July and August, it has been suggested that winter cereals, which grow mainly during the cooler, most moist part of the growing season, may be more productive than spring-grown crops on saline soils. Winter cereals grown on saline soils are, however, more susceptible to winter kill than normal. Field trials have also shown that both spring barley and oats are more tolerant of this condition than winter wheat or rye.

Diseases

Potential disease problems with winter cereals and with stubbled-in winter wheat in particular are difficult to assess, largely because of the limited track-record of these crops outside southern Alberta.

Although licenced varieties of winter wheat do not have resistance to many common rust strains, the risk of rust damage is generally low as the winter wheat matures before rust becomes a problem. However, because rust enters the southeast corner of the prairies first, a risk of rust damage exists for some years in southern Manitoba and southeastern Saskatchewan.

The incidence of burnt smut is much greater in winter wheat than in spring wheat. Seed treatment is required.

Frost

Although winter wheat is equally susceptible to late spring frosts as spring wheat, damage is rare. Earlier heading fall rye is more susceptible than winter wheat, but again damage is infrequent and generally occurs only in the more northern areas.

Early fall frosts, which are a major hazard for most spring-seeded crops in some areas, are generally of little consequence for winter cereals which mature in early August, 2 - 3 weeks earlier than spring-sown varieties. Early maturity also often translates into higher grades by avoiding poor harvest conditions which prevail later in season, particularly in the parkland area.

Winter wheat has limited seed dormancy which means that if warm, wet weather occurs when it is in the swath, sprouting and rapid deterioration in quality can result. Straight combining avoids this problem.

Yield

Yields of winter cereals, similar to those of most other crops grown on the prairies, vary tremendously from year to year and from place to place depending on local moisture conditions and soil fertility levels (Figs. 9 and 10). But, in general, if the crop survives the winter, yields of the winter cereals are about 20 to 30% higher than comparable spring-sown varieties. Since winter cereals have only a short track record outside Alberta, yield predictions for specific regions or soil types are unreliable. Moreover, because the growth periods of winter and spring wheat are not the same, there is even considerable variation in relative productivity among years and locations.

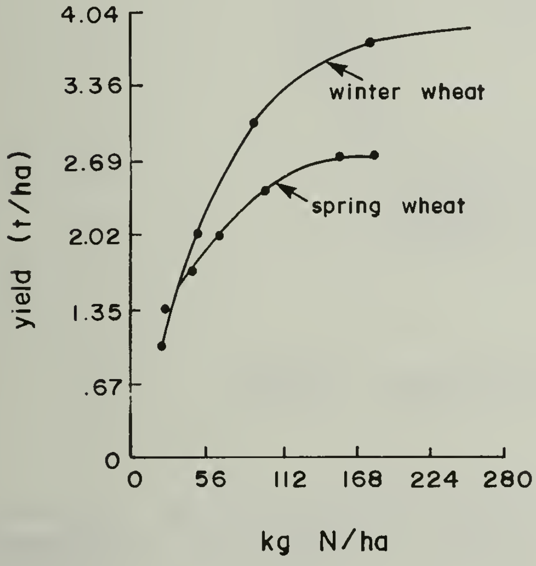

Fig. 9. Effect of available nitrogen on yield of spring and winter wheat in the parkland area of Saskatchewan, where moisture is sufficient.

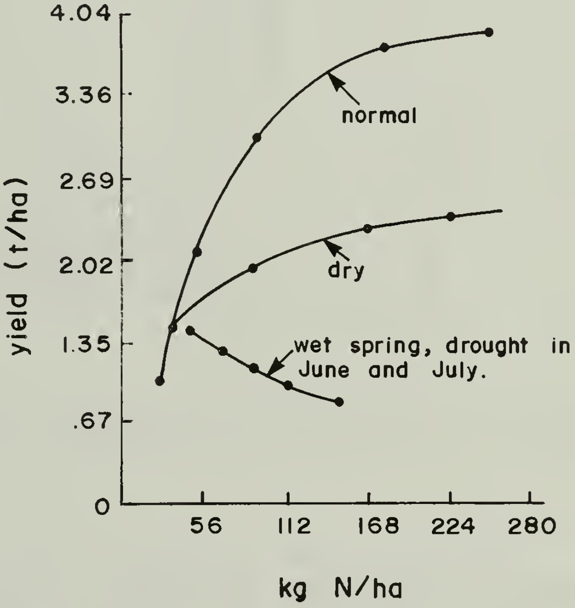

Fig. 10. Effect of available nitrogen and soil moisture on the yield of winter wheat in the parkland area of Saskatchewan.

SUMMARY

From the time of the first settlements in Western Canada, farmers have attempted to produce winter cereals. Fall rye has been grown successfully for some time, but poor market potential and resulting low prices have limited production. For winter wheat, the traditional production area has been southern Alberta where about 200,000 to 450,000 acres were seeded annually. Elsewhere, production was sporadic and largely unsuccessful due to the frequency of winter-kill. In recent years, however, with the adoption of the practice of direct seeding into standing stubble, which has substantially reduced the risk of winter kill compared to the traditional method of seeding either summerfallow or tilled stubble fields, winter cereals and winter wheat in particular have caught the imagination of many producers and the production picture has changed dramatically (Fig. 11).

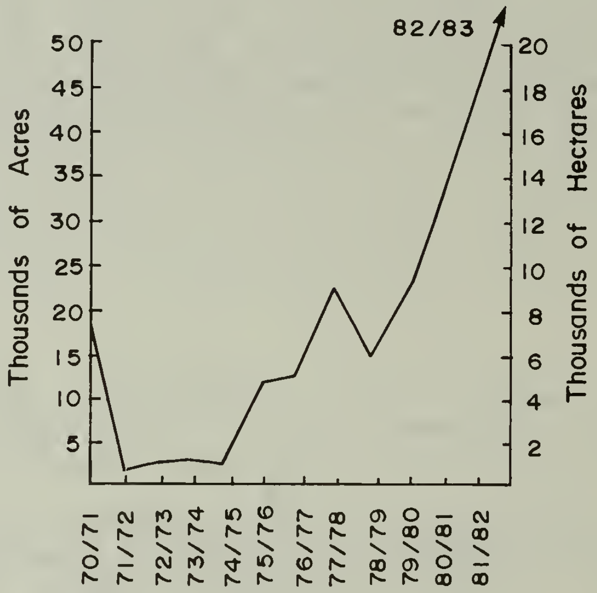

Figure 11. Winter wheat production in Saskatchewan, 1970-82.

These advantages of winter cereals over the more traditional spring-sown types have long been recognized: 1) distribution of farm labor requirements, 2) less erosion, 3) better weed competition, 4) reduced risk of loss from diseases, 5) early maturity and, 6) higher yields. However, this has not been reflected in the proportion of the area devoted to winter cereals. The major limitation to the expansion of winter wheat acreage on the prairies is the availability of 'zero' or minimum-tillage drills. Most producers do not have access to this type of seeding equipment and, without it, it is difficult to obtain proper seed placement in untilled stubble fields.